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CELL MODULE AND FUEL CONDITIONER

4TH QUARTERLY REPORT: JULY-SEPTEMBER, 1980

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October, 1980

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract DEN 3-161

for
U.S. DEPARTMENT OF ENERGY
Energy Technology
Division of Fossil Fuel Utilization
Under Interagency Agreement DE-A1-03-79ET11272



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I. INTRODUCTION

This report is for the second Phase of a six Phase program to develop commercially viable on-site integrated energy systems (OS/IES) using phosphoric acid fuel cell (PAFC) modules to convert fuel to electricity. Phase II is a planned two year effort to develop appropriate fuel cell module and fuel conditioner conceptual designs. The fuel cell module development effort comprises three coordinated tasks:

- Task 1: Design of Large Cell Stacks
- Task 2: Stack Fabrication
- Task 3: Stack Testing

The "Fuel Conditioner Subsystem Development" task is the fourth technical task of this effort. Provision for "Management, Reporting and Documentation" is included as a fifth task.

The work accomplished during this reporting period is described at the subtask level in the following section.

II. TECHNICAL PROGRESS SUMMARY

TASK 1: DESIGN OF LARGE CELL STACKS

1.1 Detailed Analytical Model

The detailed analytical model and computer code for the MK-2 design was completed this quarter. The code calculates the current density and temperature distribution in the plane of an average cell including the cooling effect of process air, fuel, and cooling air flows. The code also considers the case of cross flow of reactants for the DIGAS mode of operation. Preliminary results for the DIGAS case agree with the previous model which neglected heat conduction in the fuel flow direction.

1.2 Stack Design

Stack Measurements

Measurements of the height changes of an 80 cell stack under operating and other conditions were made and are summarized in Table I. This stack was built for an ERC in-house project and included 13 cm x 38 cm cells with Mat-i matrices and Kynol shims.

As indicated in Table I the stack (measured from end plate to end plate) height decreased during the acid filling step (line 2) and decreased further during eleven normal start-up and shut-down cycles. This is apparently due to a deformation of some components of the cells which soften or creep at elevated temperatures and, as indicated by the reduced tie bar deflection on line three, results in a reduction in the compression of the cells.

In an effort to determine the stack height under simulated operating conditions, the stack was heated to 178°C with the manifolds removed and the tie rods exposed to room temperature (line four on Table I). The stack height increased ~.07 cm from its room temperature height (line three) but was still ~.096 cm shorter than its initial height at room temperature although the compression was coincidentally the same (~.32 cm deflection of tie bars). When cooled to room temperature, the stack

TABLE I

13 x 38 cm 80 - CELL, MAT-1 STACK

CONDITION OF THE STACK	TEMP.	HEIGHT OF STACK END PLATE TO END PLATE in. (cm)	HEIGHT DECREASE in. (cm)	CUMMULATIVE HEIGHT DECREASE in. (cm)	DEFLECTION OF TIE BARS in. (cm)
1. Stack assembled and compressed.	Room Temp.	20.856 (52.975)	---	---	1/8 (0.32)
2. Stack heated for acid addition.	74°C	20.828 (52.903)	0.028 (0.072)	0.028 (0.072)	---
3. After eleven cycles.	Room Temp.	20.785 (52.795)	0.043 (0.109)	0.071 (0.180)	5/64 (0.20)
4. Heated.	178°C	20.818 (52.879)	-0.028 (-0.072)	0.038 (0.096)	1/8 (0.32)
5. Cooled.	Room Temp.	20.774 (52.767)	0.044 (0.112)	0.082 (0.208)	Less than 5/64
6. Compressed.	Room Temp.	20.699 (52.575)	0.075 (0.191)	0.157 (0.400)	1/8 (0.32)

height was less than its previous value (line three) indicating that permanent setting of some material in the stack was still occurring after twelve cycles. When the tie rod tension was adjusted to obtain the same pressure as initially applied to the cells, the measured cumulative permanent set was 0.4 cm (line 6) or 0.005 cm per cell.

Heat-Treated Plates

Under the supporting Technology Contract (DEN3-67) and in-house programs, ERG has developed a process for heat treating bipolar plates. The heat treated plates have lower electrical resistivity and the performance of stacks built with them appear to stabilize at much higher level (\approx 80 mV/cell higher) than those with untreated plates. Based on the progress made with the process, we plan to heat treat the bipolar, cooler and unipolar end plates for all stacks after 561. To this end, some critical experiments are being carried out to define the treatment required for the MK-2 bipolar and the MK-1 and MK-2 cooler plates.

Stack Compression

Previous stacks and those being built under this program are compressed by a combination of tie bars and tie rods developed for smaller (13 x 38 cm cell stacks) and different applications. Several modifications are being evaluated for use in short (23-cell) and simulated (5-cell) stacks.

The cross configuration tie bars demonstrated under the supporting technology program (DEN3-67) provide greater access to the air and fuel manifolds. However, the tie bar length required for 31 x 43 cm cells results in a 1.8 cm deflection for a compression of 380 kPa. As shown in Table II thicker tie bars (3.2 cm compared to the present 2.2 cm) will have much less deflection (0.6 cm at a compression of 380 kPa) and a higher safety factor (3.2 compared to 1.6).

TABLE II
PRESENT AND PROPOSED CROSS TIE-BARS AT
DIFFERENT STACK COMPRESSIONS

NOMINAL STACK COMPRESSION, kPa	PRESENT TIE BARS (Cross section 2.2 x 3.2 cm)		PROPOSED TIE BARS (Cross section 3.2 x 3.2 cm)	
	DEFLECTION, cm	SAFETY FACTOR	DEFLECTION, cm	SAFETY FACTOR
345	1.67	1.73	0.57	3.53
380	1.84	1.57	0.63	3.21
414	2.01	1.44	0.69	2.94

AISI-01 Tool Steel

Yield stress = 1.4×10^6 kPa at 47 Rockwell hardness

The tie rod/tie bar compression provides no positive means of compensating for expansion or contraction of the cell components. We are evaluating the use of Belleville washers (which provide a constant force over a range of deflections) on the tie rods to maintain stack compression. The Belleville washers being considered were sent to an independent testing laboratory for experimental determination of load deflection characteristics. The experiments were conducted on single washers and on series and parallel groupings of washers. This information and the strain measurements to be made on Stacks 559 and 561 (incorporating strain gauges) will be used to select the proper configuration of washers to maintain the desired compression.

Material Characterization

Thermal distortion measurements of miniature (6.25 cm square) stacks of "dry" fuel cell components were made to determine their thermal behavior. This data is needed to design a stack enclosure to accommodate the dimensional changes over the operating temperature range and life of the stack. The data of these tests are summarized in Table III. Some of the data are plotted in Figure 1. The small diagrams next to test numbers in the figure depict the composition of the test articles. For example, the test articles used in tests 6 and 7 were bipolar plates only; whereas in tests 8, 9, 10 and 11 they were sandwiches of bipolar plates, anode, matrix and cathode materials.

In the initial tests, a hysteresis effect was noted; during cooling to room temperature, the test articles contracted more than they had expanded during the heating cycle (e.g. Test 6). Since the specimens were exposed to the lab environment for prolonged periods before or between tests, the hysteresis effect was attributed to moisture absorption. This hypothesis appears justified, since rapid repetition of the test results in a reduction or elimination of the effect. Test 7 which was a repeat of and immediately followed Test 6 provided supporting evidence of this hypothesis. The plot of Test 7 also indicates a thermal expansion and contraction behavior which is normally observed with solids.

TABLE III
THERMAL EXPANSION/CONTRACTION MEASUREMENTS

Bipolar Plate Specimen	Test Number	Test Article Description	Applied Pressure kPa Kilo-Pascal	Thermal Expansion/Contraction in 10^{-6} m/m			Comments
				Heating 25°C to 200°C	Cooling 200°C to 25°C		
1	1	Bipolar Plate, Only	None	1,800 2,200	- 1,200 - 400	Contracts Beyond Original Size, When Cooled to 25°C * Contraction Significantly Less	
2	1	" " "	"	2,800	- 1,000	Specimen 2 Behaves Similar as Specimen 1	
2	2	" " "	"	2,600	- 400	*	
3	2	" " "	"	3,000	- 1,400	Specimen 3 Behaves Similar as Specimen 2	
3	3	" " "	"	3,800	- 200	*	
3	5	" " "	414	3,400	- 600	*Same Specimen 3, Applied Pressure, Test 4 Failed	
3	6	" " "	414	2,400	- 1,200	Specimen Sitting Out For Days, Absorbed Moisture	
3	7	" " "	414	3,300	0	*	
3	8	Bipolar Plate+Cathode+Matrix+Anode	414	- 5,400	- 9,000	Cathode+Matrix+Anode Added, Same Bipolar Plate, Severe Yielding When Heated, Almost No Expansion	
3	9	" " " " "	414	200	- 3,300	*Slight Expansion, Specimen Still Yielding	
3	10	" " " " "	414	- 7,000	- 12,000	Same Bipolar Plate But New Anode, Matrix and Cathode Added, Results Similar to Test 8	
3	11	" " " " "	414	600	- 3,400	*Results Similar to Test 9	
3	16	" " " " "	414	- 2,800	- 8,300	*Dilatometer Malfunctioned on Previous Tests, Held Specimen at 200°C for Extended Period Until Yielding Stopped	
3	17	" " " " "	414	2,400	- 1,300	*Repeated Test 16, Same Components, Expected No Additional Yielding, Expectation Proved Incorrect, Except at 200°C	
3	18	" " " " "	414	2,800	- 1,100	*Repeated Test 17, Same Components, Behavior Similar to Test 17	

*Test Performed Immediately Following the Preceding Test, To Prevent Specimen from Absorbing Moisture From the Atmospheric Environment.

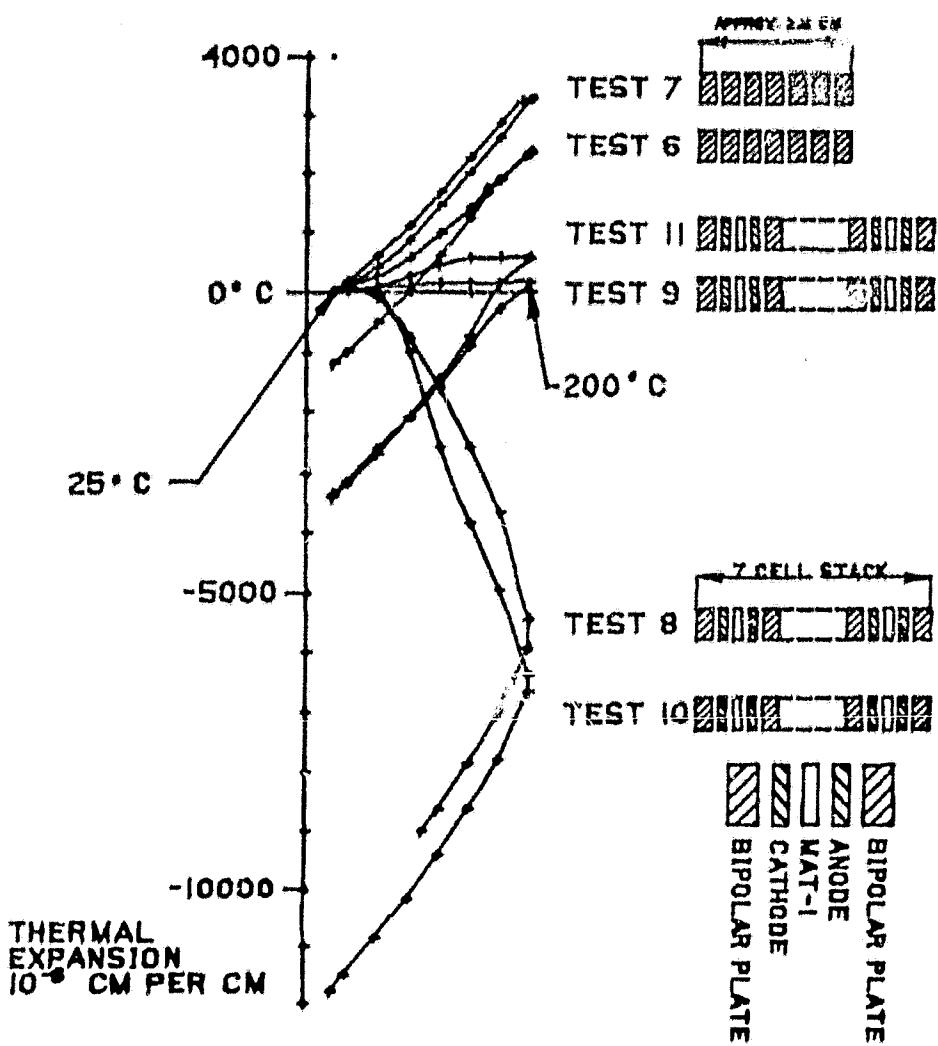


Figure 1. Thermal Distortion Measurements on Miniature Stacks

The behavior changed drastically when the anode-matrix-cathode "sandwich" was added. During Tests 8 and 10, the bipolar plate's expansion was totally absorbed as the sandwich apparently "yielded" or "flowed." The same bipolar plate test articles were used for both tests, but a new anode-matrix-cathode sandwich was used for Test 10 to learn if the previously observed behavior would be observed again. Tests 9 and 11 repeated tests 8 and 10 with the used sandwiches. The expectation that the plots of Tests 9 and 11 would have little or no hysteresis since the materials were already compressed, proved incorrect and lead to the hypothesis that the yielding was time dependent. Test 16 was performed with the temperature held at 200°C until all yielding had ceased. The data of Test 16 are plotted in Figure 2. At the lower right is a three dimensional diagram of (and shown expanded in Figure 3) temperature, time, and expansion contraction. The temperature reached 200°C at 70 minutes and was held at this level for 155 additional minutes. Contraction slowed and finally stopped near the end of this period (see arrow Figure 3). Further contraction (caused by cooling, not yielding) occurred as the test articles cooled to room temperature. A very slight expansion occurred at the start of the heating cycle.

Because it appeared that all the yielding had occurred during Test 16, no hysteresis was anticipated for Test 17 which used the same components. Again this proved to be incorrect, but the behavior was more normal and was similar to that observed in Tests 5 and 6 (Figure 4). No contraction was observed when the temperature was held at 200°C for an extended period.

Conclusion

After several thermal cycles from ambient to operating condition (200°C) almost all yielding of the anode-matrix-cathode sandwich has taken place. Subsequent thermal expansion and contraction of the bipolar plate-anode-matrix-cathode composite is very similar to the thermal expansion and contraction of the bipolar plates by themselves. If the enclosure can be designed to accommodate this thermal behavior, the

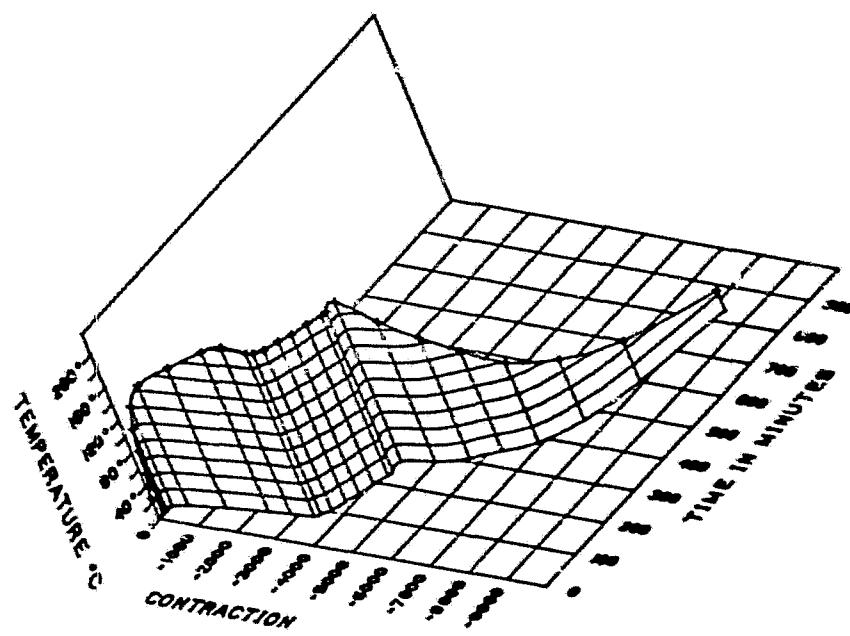
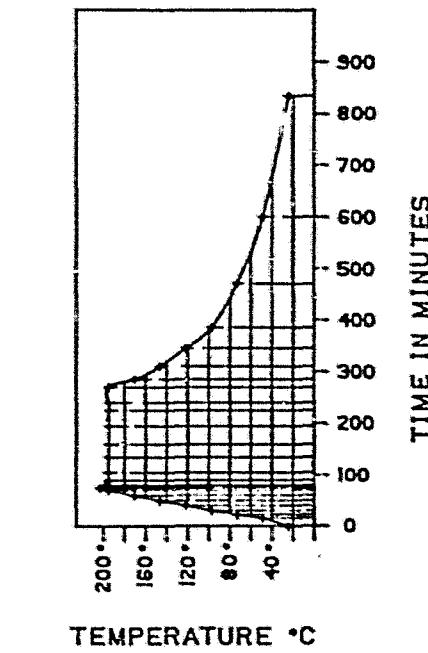
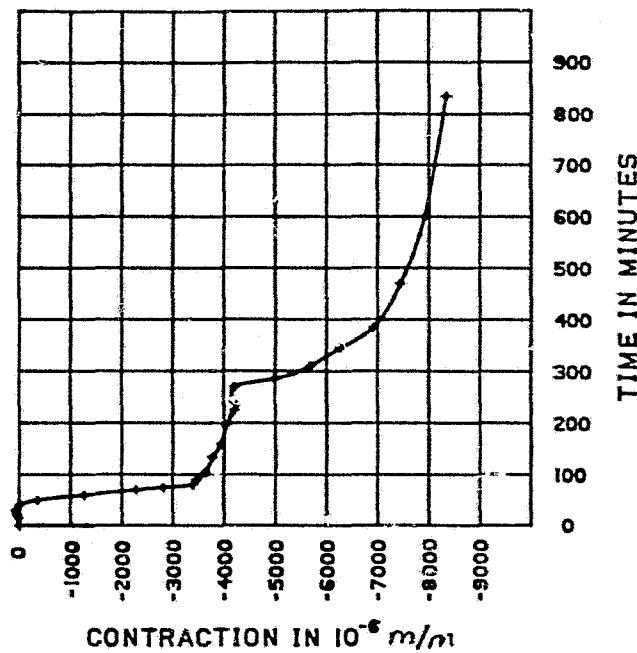
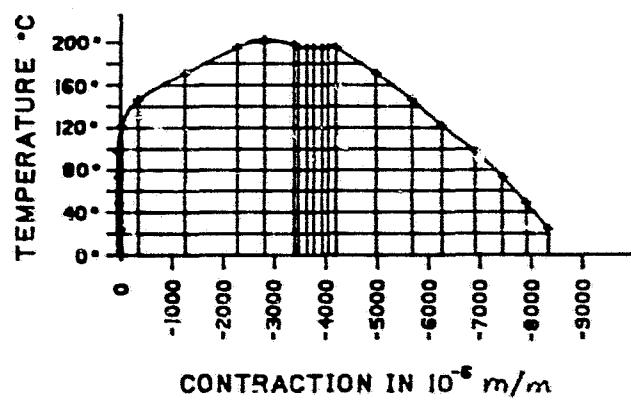


Figure 2. Test 16 Data

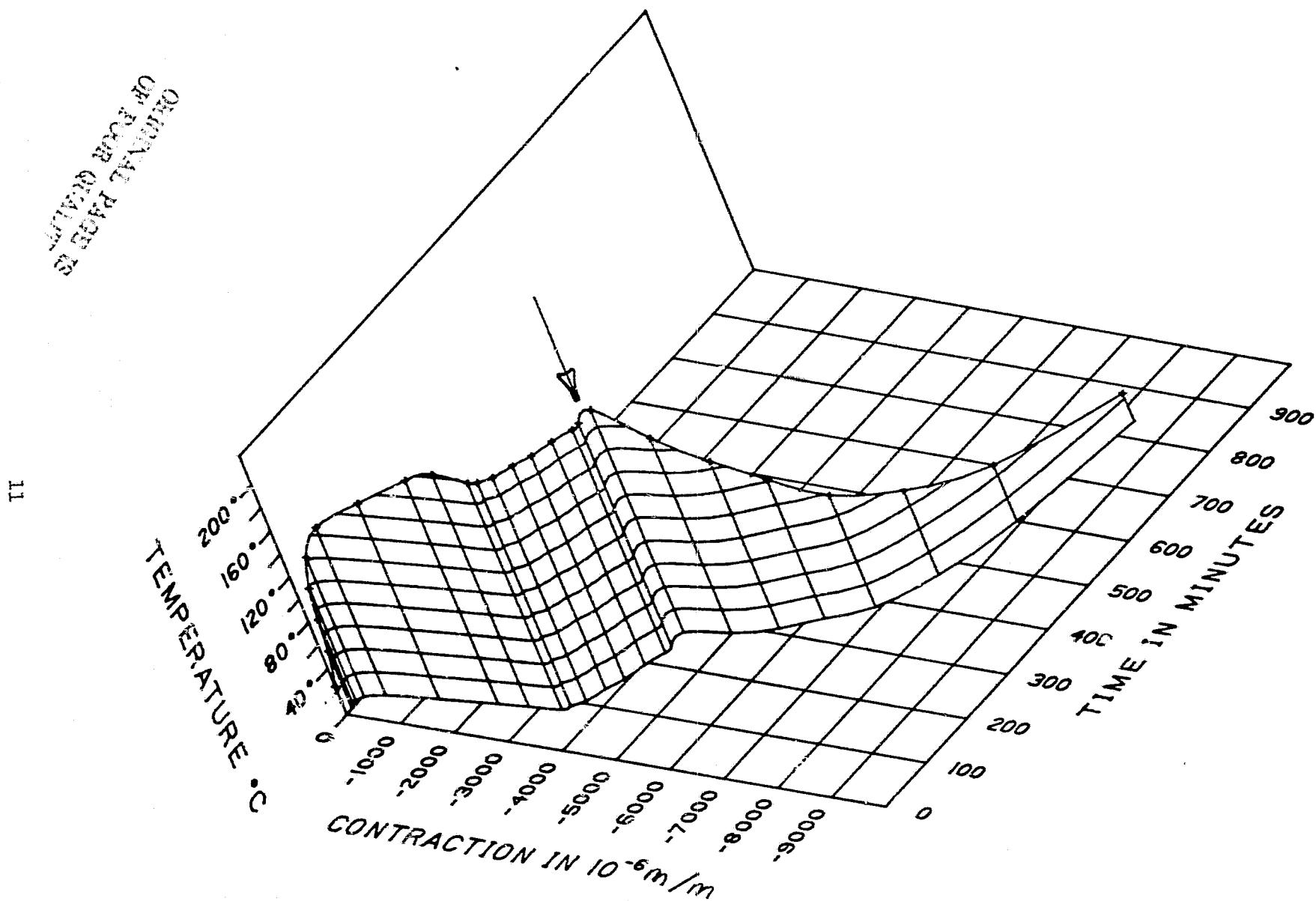


Figure 3 Expanded 3D Plot of Test 16

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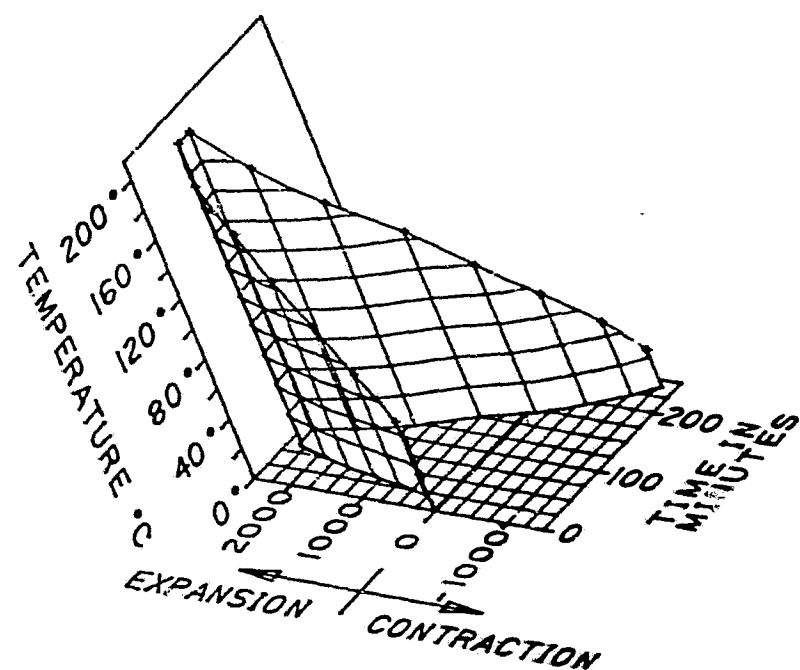
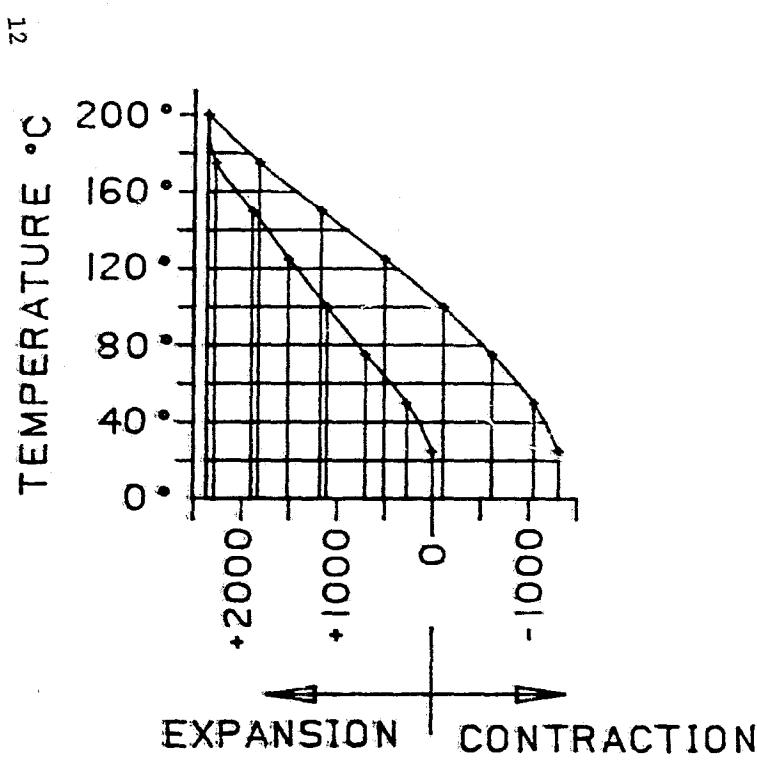
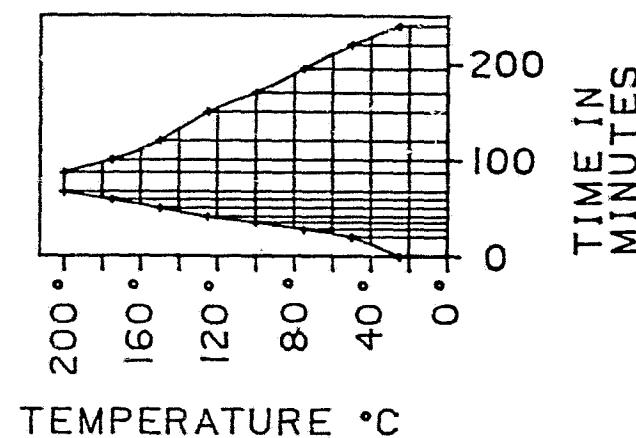
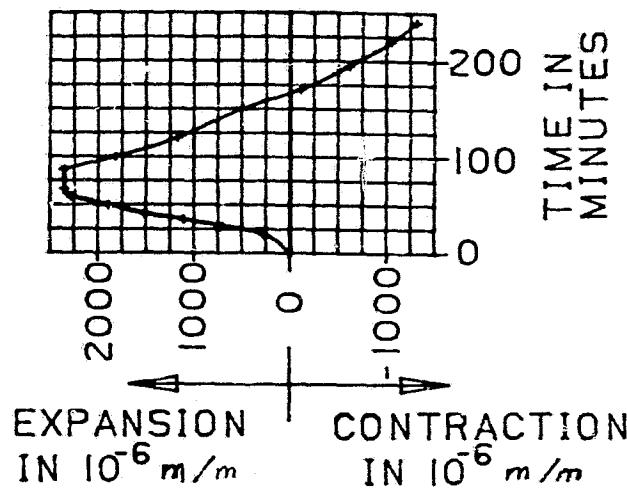


Figure 4. Test 17 Data

manifold-to-stack seal problem will be less severe since the calculated difference in thermal expansion between an aluminum manifold and a 150 cell stack is only 0.8 mm for a 190°C temperature rise. This number is small because the expansion coefficients of the bipolar plates and aluminum are closely matched.

To achieve this, the stack could be assembled without the manifolds, the pressure applied and the stack subjected to several thermal cycles until most of the yielding (say 95%) has occurred. When the manifolds are attached, the seals would not be subjected to the stack's contraction which occurred during the initial yielding.

1.3 Full Scale Module Design

Stack-Manifold Seal

The cost evaluation of various gasket/seal shapes was completed. The most economic and functional seal is made of a solid fluoroelastomer, such as viton, has a 0.54 cm diameter circular cross section, is continually extruded and wound on a spool. During stack assembly the material is cut to the proper length and its ends are joined with a cement, such as Eastman 910, in a joining fixture. A 30 KW stack can be sealed for \$1.56 per kilowatt using this type of gasket.

TASK 2: STACK FABRICATION

2.1 Methods and Approach

Cooling Plate Assembly

Various types of conductive materials were tested for bonding the cooling plate halves. The best results were obtained with an innovative method which is described in a patent disclosure to be submitted to the NASA Project Manager separately.

Table IV compares the voltage differences of cooling plates made with this method with those of plates joined by two other methods. The measurements were made using the setup shown in Figure 5. The voltage lead numbers in the table correspond to the points in the figure consecutively from right to left.

In making the voltage measurements, a force corresponding to a nominal compression of 340 kPa was applied and a known current was sent through the plate subassembly.

As shown, the voltage drops were dependent on position, indicating significant variations in contact resistance and/or current densities over the plate areas. However, the relative values were reproducible and show that the innovative method results in application contact resistances that are comparable to or better than those obtained with backing paper. Since backing paper compromises cooling plate design, the innovative method was used for Stacks 559 and 561.

Electrolyte Filling

During assembly of Stack 560 (a MK-2 design, 5-cell stack) the bipolar plates were found to be incorrectly machined and the stack was used to test acid-filling Schema 2*. After heating the stack to $\sim 100^{\circ}\text{C}$, acid was fed at a rate of ~ 10 cc/hr. Over a period of five days, 114.3 cc of acid was fed to the stack and 88.7 cc came out, for a net addition of 25.6 cc (~ 5 cc/cell). Negligible weeping was observed during

* DOE proprietary

TABLE IV

VOLTAGE DROP MEASUREMENTS OF COOLING PLATE ASSEMBLY

 $i = 10$ amps

RUN:	POSITION OF VOLTAGE LEADS	1	2	3	4	5	6	7	8
<u>No. 1</u> Sanded and cleaned faces of cooling plate halves	Voltage Drop, mV	5	10	12	8	7	7	8	5
<u>No. 2</u> Backing paper between cooling plate halves	Voltage Drop, mV	1	3	4	4	4	4	3	2
<u>No. 3</u> Innovative method	Voltage Drop, mV	6	1	1	3	5	4	5	7

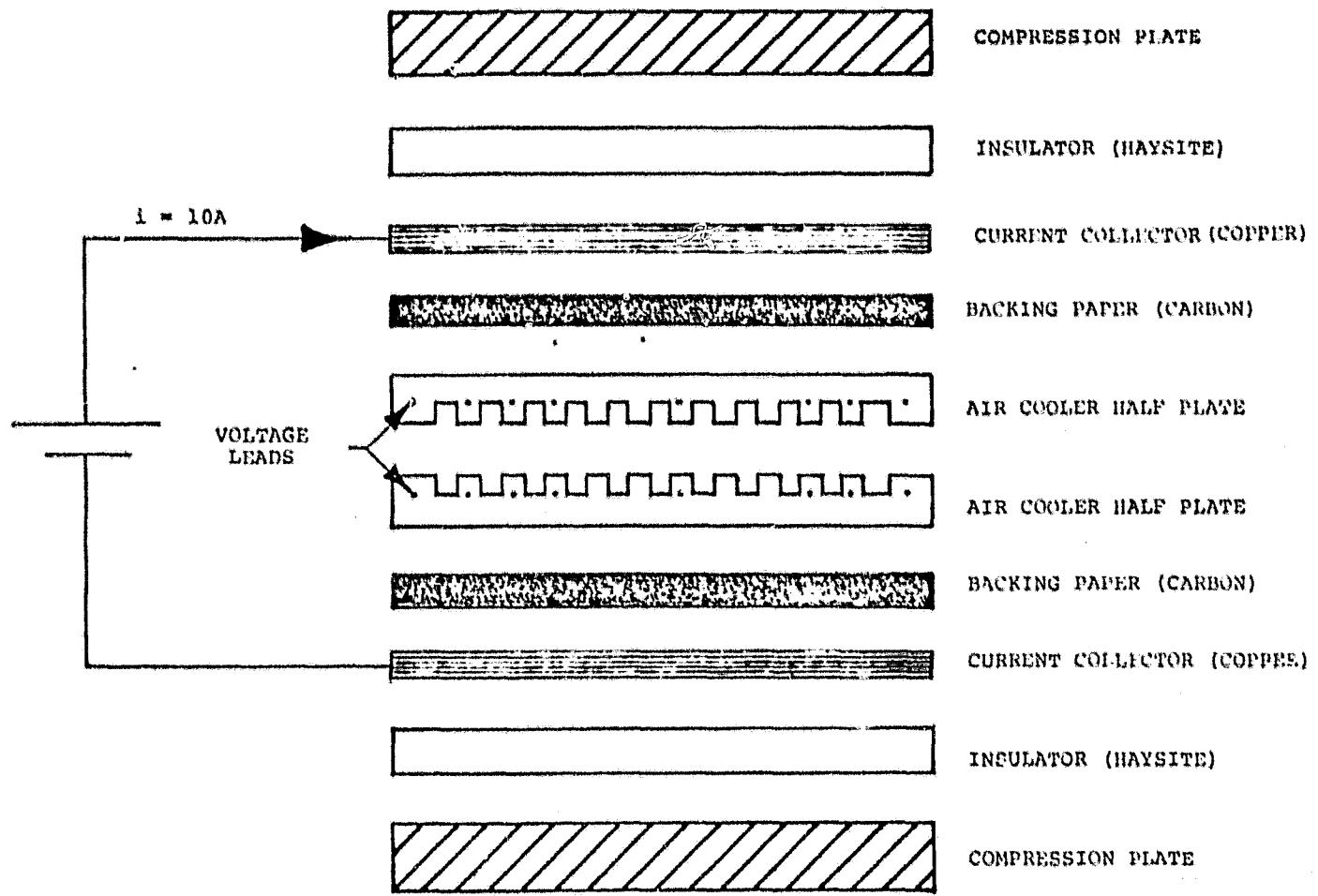


Figure 5 - EXPERIMENTAL SETUP FOR RESISTANCE MEASUREMENT

this period. Acid addition was discontinued when the rate of acid takeup by the stack decreased substantially and the stack was disassembled. All components were found to be in good condition. This stack was "wet assembled" and each cell initially had 45 cc of acid.

Based on these results and those of Stack C**, the viability of Scheme 2 at least with shorter stacks was established.

2.2 Simulated Stacks

Stack 560 (5-cell MK-2)

To replace the incorrectly machined bipolar plates, new blanks were sent to the vendor for machining and five machined bipolar plates were received. The end plates are being machined and electrodes and matrixes are being fabricated. Once the end plates are received, they will be heat-treated along with the bipolar plates. Stack assembly is anticipated at the end of October.

2.3 Short Stacks

Stack 559 (23-cell, MK-1)

Stack 559, the MK-1 short DIGAS stack, was assembled on September 8, 1980. The stack, was wet-assembled with 45 cc of H_3PO_4 placed on the electrochemical components (matrix and electrodes) of each cell in a dry room. On the following day, the stack was compressed to a nominal pressure of 340 kPa as measured by strain gauges on the tie rods.

The stack was heated to $\sim 100^\circ C$ and acid addition was initiated at a rate of ~ 10 cc/hr, using a drip method. When acid began to weep out at points near the acid fill tubes the compression points were moved closer to these points and the weepout decreased significantly. Acid addition was discontinued and efforts to determine the flow limiting condition were initiated when it became clear that the stack could not accept this flow rate.

** Reported in the Second Quarterly Report

Stack 562 (23-cell MK-2)

During this quarter, a decision was made to use heat-treated bipolar and cooling plates in 562. Fabrication of cell electrochemical components is in progress. The blank plates were molded and are being machined by a vendor. When the machined plates are received, they will undergo heat-treatment and the cooling plates will be assembled. Final stack assembly should take place approximately three weeks after the machined plates are received since the fabrication of the other electrochemical components should be completed by then.

Stack 563 (23-cell MK-1)

Stack 563 will be a MK-1 short stack with heat-treated bipolar and bipolar/cooling plates. Fabrication of the plates and other cell components is in progress.

TASK 3: STACK TESTING

3.3 Short Stacks

Stack 425 (23-cell MK-0*)

Since ERG had no plans for further testing of Stack 425 which was fabricated as part of their Technology Contract, we obtained permission to test it in the OS/IES Simulation Test Loop. The tests encompassed measurements of the stack mechanical and electrical characteristics as described below.

In order to separately measure the forces applied to the cells and the manifolds by the tie rod/tie bar compression system, strain gauges were installed on the tie bars and manifolds and the tie rods were replaced with strain gauged tie rods. In replacing the tie rods precautions were taken to retain stack compression and the strain gauges which were installed on the tie bars showed no change during this operation.

In order to measure changes in stack height, 8 pads were installed on the stack compression plates (4 on each plate). Using these and a large micrometer, stack height changes could be resolved to $\pm .005$ cm.

With this instrumentation we determined the following mechanical characteristics of Stack 425:

1. The force applied to the stack by the tie rods was 28700 N as received.
2. Following several heating and cooling cycles of the stack, the manifolds do not restrain the stack or carry any of the force applied by the tie rods/tie bars. Apparently the Viton gasket yields or flows loosening the manifold bolts.
3. The loaded stack expands vertically .0046 cm for every 10°C increase in temperature.
4. At a temperature of 107°C the stack height decreases approximately 0.014 cm for each 10000 N increase in applied force.

* Conventional DIGAS stack.

Electrical Tests

The planned electrical testing of stack 425 was curtailed when we found that one cell operated in reverse at stack currents of 52 mA/cm^2 and were unable to correct its performance.

Hydrogen sensitivity tests revealed that this cell (the ninth from the bottom of the stack) was not getting adequate fuel. When we removed the fuel manifolds we found that all of the bipolar plate channels were filled with liquid (most likely a mixture of electrolyte and water). To rehabilitate the cell we cleaned all of the channels with soft cotton string. We also checked all other fuel channels and all cell air channels and found little or no obstructions. In subsequent tests the voltage of the cell was approximately one half of the other cells at 40 amps. Electrical tests on this stack were terminated since the anomalous performance of this cell results in hydrogen generation on the air side and a substantial distortion of the current density distribution in the stack. One of the major objectives for the electrical test was the measurement of cell temperature with these cooling plates under OS/IES conditions. The distorted current density distributions makes it impossible to interpret the temperature profile measurements.

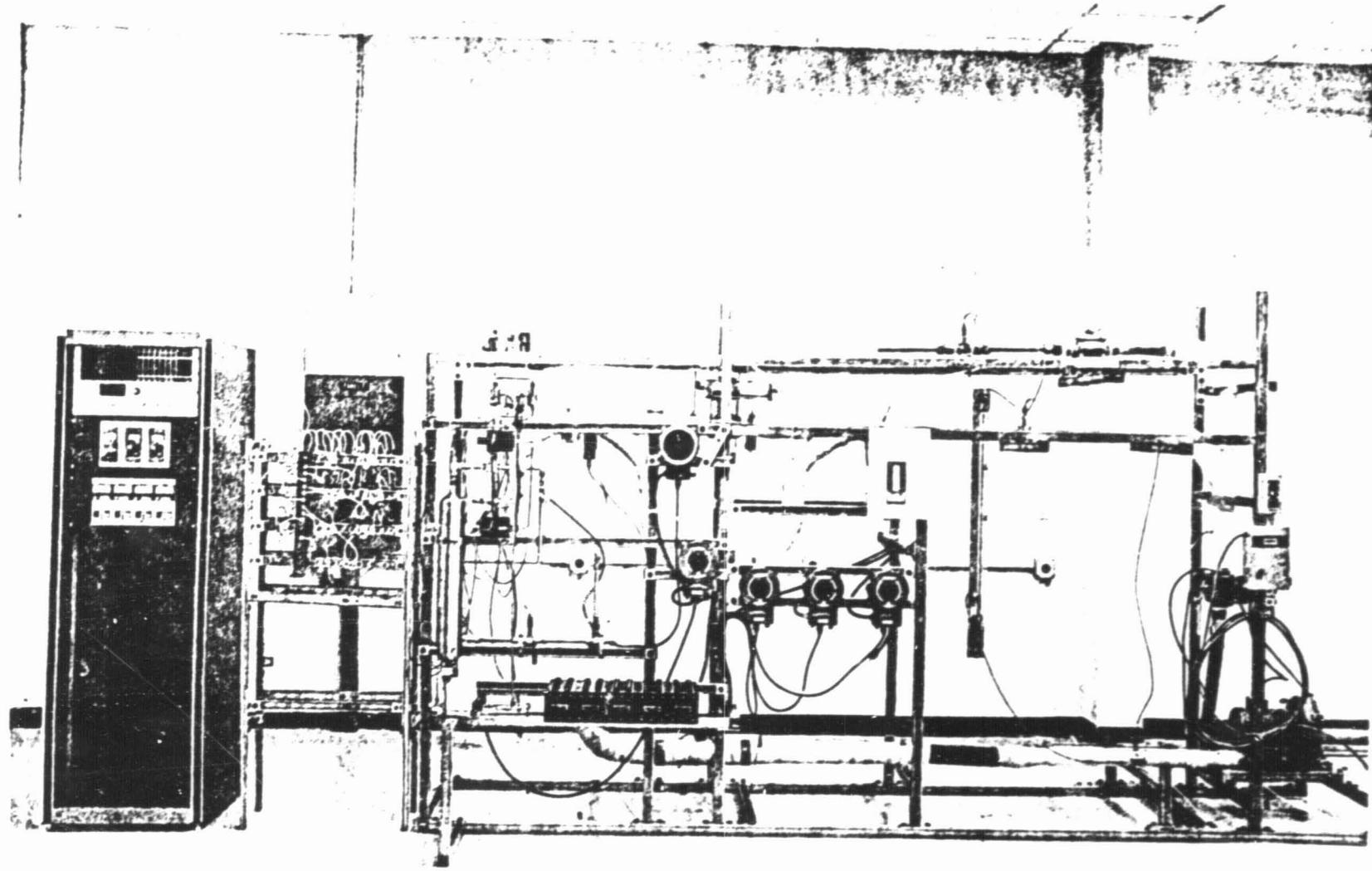
3.4 Test Stand Design and Construction

The 2kW Test Facility

Construction of the 2 kW test facility (shown in Figure 6) was completed. At present the checkout dry runs are being conducted and minor adjustments are being made. The test facility is expected to be ready for use in the latter half of October.

8 kW Test Facility

Placement of purchase orders for the 8 kW test facility continued and some equipment was delivered in the second half of September. Thus, there will be good continuity from the 2 kW test facility construction to the 8 kW facility construction.



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Figure 6 - 2kW Test Facility

The following two changes from the description presented in the Second Quarterly Report will be incorporated.

1. An air to air heat exchanger will be used in place of the air to water heat exchanger for the following reasons.

- The air to air system will be less expensive and simpler to maintain and control since the air flow rate can be reduced to control the recycle stream temperature at part load. (In the water system, boiling will occur if the flow is reduced too far). This eliminates the need for a bypass loop around the heat exchanger which saves space and reduces the number of tees, valves, flanges, etc.
- Since an essentially infinite supply of cool air is available, there is no need for a secondary heat exchanger which would be required with a water cooled system. This greatly reduces the amount of plumbing required and eliminates the secondary heat exchanger. Of course it also eliminates the need to protect a heat exchanger and piping from freezing during cold weather and the need to provide for expansion and contraction of the cooling fluid.
- The reliability of the system is improved since the possibility of leaking water into the recycle stream and other leak problems are eliminated.
- The flow rate of the recycle stream through the blower is now independent of the need to control temperature simplifying the blower control problem.
- Energy can be conserved by using the cooling stream to provide space heating for the building during the heating season. Of course, it will be exhausted outside of the building during the cooling stream.

2. An Annubar flow meter will be used to measure gas flows instead of the turbine meters originally proposed.

The Annubar meter operates on the same principle as a pitot tube but uses 4 pressure ports which are located (using Chebychef calculus) to give an appropriate average total pressure. The claimed error is less than $\pm 1\%$ of the indicated value.

The Annubar sensor is simpler, cheaper, more reliable and causes a smaller pressure loss than the proposed turbine meter but may require a longer straight run of pipe. However, the reduced pressure drop reduces the required fan power from 15 to 5 hp at the highest flow condition.

TASK 4: FUEL CONDITIONER DEVELOPMENT

4.1 Fuel and Water Definitions

See Quarterly Report No. 2, Section 4.1.1 and Table VII for fuel and water definitions used as the basis for Task 4.2 and Task 4.4.2 in this report.

4.2 Operational Requirements Definition

New values of state points were calculated for full load (120 kW DC) and 1/3 load (40 kW DC) operation for the system configuration shown in Figure 7. This configuration is continuously evolving as the operational requirements are defined. The requirements addressed this period were the need to effectively use the heat in the reformer product gas, the reformer combustion gas, and the warm air from the DIGAS cooled fuel cell stacks and incorporate the heaters and controls required to start the system and to operate efficiently at part load. In evaluating part load operation, extended surface exchangers and packed bed design of the reformer and shift converter were assumed. The exchangers were assumed to be counter flow with finned surface tubes except for condensing service or hot water service.

Analyses of full load and part load performance were made assuming 10% (by volume) of the shift converter outlet was recycled and mixed with the natural gas supply to provide H_2 for the hydro-desulfurizer/zinc oxide reactors. Fortunately, the effect of this recycled H_2 , CO, and CO_2 on reformer performance turned out to be small since, without recycle H_2 , the desulfurizer would require a m. h larger charge of zinc oxide.

For the flow geometries assumed, several heat exchangers had laminar flow on the inside of the tubes at full load. Calculations were made for two heat exchangers to see what aspect ratio (height to width to length) would be necessary to force turbulent flow on the tube side. For the tubing and flow geometry selected (tube O.D. = 11 mm, fin O.D. = 22 mm), the length to height and length to width ratios were greater than 10:1. Such an aspect ratio may be impractical since a more reasonably

proportioned heat exchanger could be less expensive, even though its surface area was larger.

The 1/3 load analysis of the system took into account the change in electrical efficiencies of both the fuel cell and the power conditioning equipment. This resulted in a slight improvement in overall efficiency, so that the part load H₂ flow was less than 1/3 of the full load H₂ flow. Reformer outlet temperature would normally have increased with decreased throughput due to improved heat exchange effectiveness. Such a change would have allowed a better methane to H₂ conversion, but would have decreased the spent fuel heating value and quantity beyond the point where self-sustaining reformer operation was possible. To prevent this, the maximum temperature of the reformed gas was kept nearly constant to assure uniform reformer outlet composition regardless of flow rate. The method chosen to achieve this, was to monitor the catalyst bed outlet temperature and regulate the combustion air flow rate, to control the combustion temperature which, in turn, maintains the desired catalyst temperature. Similarly, other temperatures in the system must be maintained close to the temperature specified for full load to assure effective system operation. Examples of such points are: condensate and feedwater heater outlets, natural gas and superheated steam entering the reformer, and spent fuel entering the reformer burner. These temperatures are regulated by thermostatically controlled valves or dampers which bypass hot side flow around the heat exchanger.

For components without bypass control, an approximate relationship for the change in heat transfer coefficients as a function of mass flow on each side of the surface was derived from data in "Compact Heat Exchangers," by Kays and London. Based on calculated changes in heat transfer coefficient and using NTU-heat exchanger effectiveness relationships, the outlet conditions from these components were determined at part load. Tables V and VI show full and part load performance for the components in Figure 7.

TABLE V

OS/IES Full Load Performance (120 kW DC)

Equipment Item No.	Hot Side (°C)		Cold Side (°C)		Mass Flow (kg/hr)		Thermal Load (kJ/hr)
	Inlet	Outlet	Inlet	Outlet	Hot Side	Cold Side	
E-1	393	230	60	316	290	214	56000
E-2	166	248	21	149	103	33	10400
E-3	328	312	149	204	103	33	4750
E-4	388	328	177	316	103	79	17100
E-5	232	166	38	100	103	71	18400
E-6	230	121	27	82	290	154	35800
E-7	282	232	38	85	103	71	14000
R-1	1200	393	204	388	290	103	335000
CD-1	177	37	10	63	564	592*	242000
CD-2	248	54	10	63	103	322*	71200
B-1	177	158	85	149	7220	71	160000
SH-1	312	282	149	204	103	71	8500
C-1	158	127	27	82	7220	1230	287000
C-2	100	38	21	32	71	1080	18500

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*Supplemented by cooling tower water during low domestic hot water demand periods.

TABLE VI

OS/IES Part Load Performance (1/3 Power)

Equipment Item No.	Hot Side (°C)		Cold Side (°C)		Mass Flow (kG/hr)		Thermal Load (kJ/hr)
	Inlet	Outlet	Inlet	Outlet	Hot Side	Cold Side	
E-1	393	227	60	321	65	48	12900
E-2	186	232	21	181	23	5	2950
E-3*	328	321	181	204	23**	5	470
E-4*	388	328	177	316	23**	18	3850
E-5*	253	186	38	100	23**	16	4150
E-6	227	121	27	82	65	34	7910
E-7*	302	253	38	85	23**	16	3150
R-1	1200	393	204	388	65	23	75400
CD-1	177	37	10	63	127	247	54500
CD-2	232	54	10	63	23	73	16000
B-1	177	156	85	168	1620	16	38300
SH-1*	321	302	168	204	23**	16	1900
C-1	156	127	27	82	1620	277	64500
C-2	100	38	21	38	16	242	4160

*Utilizes bypass control of hot fluid to provide required cold side outlet temperature.

**Combined mass flow through heat exchanger and bypass valve.

The spent air leaving the fuel cells contains trace amounts of phosphoric acid vapor. If the amount of acid in this air is assumed to be approximately 2 ppm by weight of P_2O_5 (H_3PO_4 dissociates in the vapor phase according to the equation $2H_3PO_4 \rightarrow P_2O_5 + 3H_2O$), there will be about 400 ppm of acid in the water condensed out of the spent air stream. Such contamination would require a fresh ion exchange resin bed to be installed in the water treating system at least once every week. If, as is indicated in UTC's latest annual report for their 40 kW program, it is possible to remove 90% or more of the P_2O_5 in the spent air by partial condensation, then the ion exchange bed life could be extended to over two months. During September, process calculations indicated that it would indeed be possible to remove 90% or more of the vapor phase P_2O_5 by condensing a small part of the water content of the spent air. Vapor/liquid equilibria for the $H_3PO_4/H_2O/P_2O_5$ system verify the possibility of such removal in principle. The partial condenser requires very effective contact between the spent air and the acid condensate to achieve a close approach to equilibrium acid concentration. Its configuration to achieve good vapor/liquid contact, its materials of construction to permit effective heat transfer without corrosion, and how to control it to achieve sufficient P_2O_5 removal from the gas with a maximum acid concentration, should be the subject of future experimental work. Such work could be performed in the next phase of OS/IES development, with test work on the prototype system using the present design proceeding in parallel with test work on an improved design for the water recovery condenser that would incorporate an initial "acid trap" partial condenser and condensate disposal/reuse scheme.

4.3 Steam Reforming Catalyst Data Base

The methane steam reforming experiments for four different reforming catalysts (Catalyst 100, UC G-91, UC C-11-9-02 and Katalco 23-1) in crushed (0.5 mm) and pelleted form were completed. The results of these experiments are shown in Figures 8 through 12 and a comparison of the four catalysts is presented in Table VII and summarized as follows:

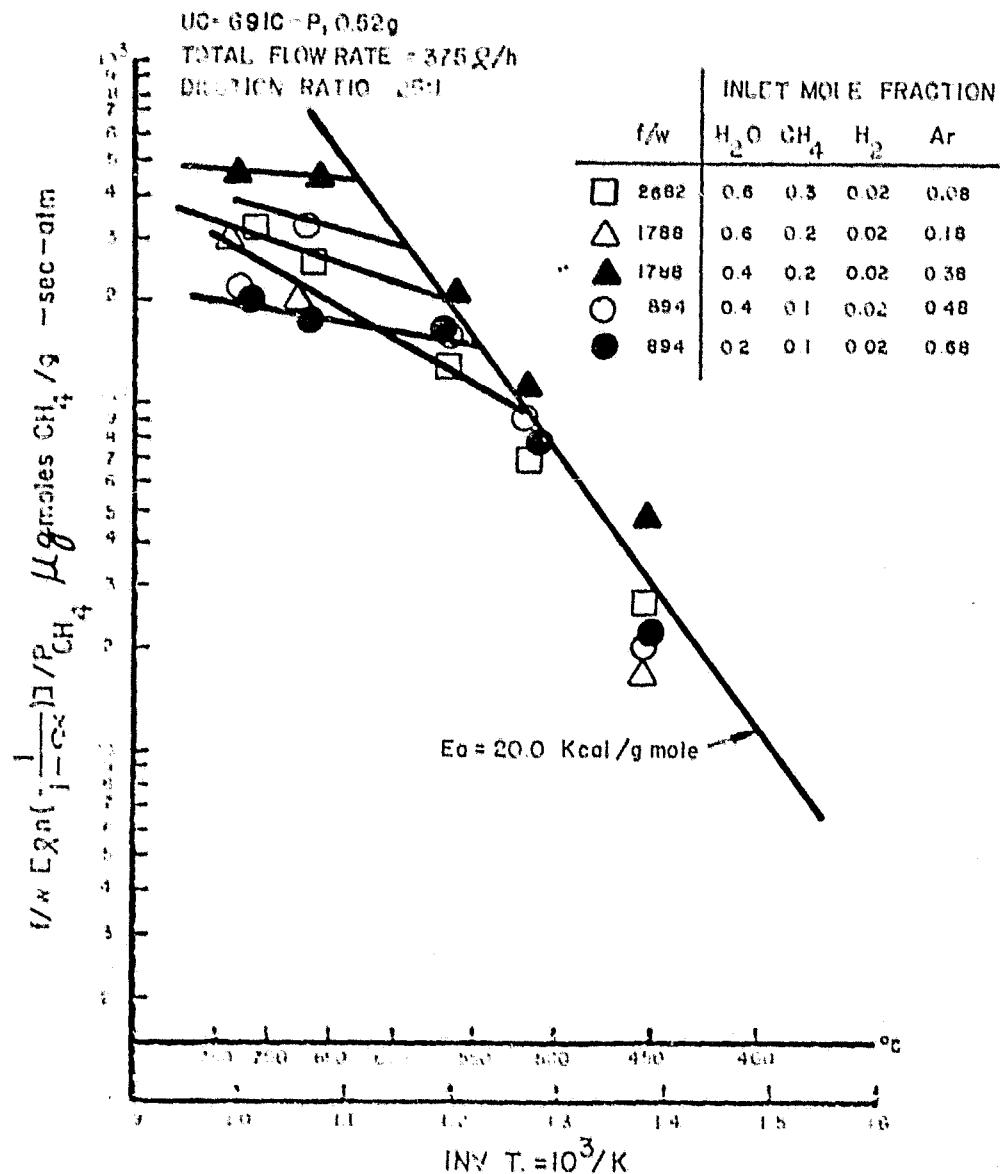


Figure 8 - TEMPERATURE DEPENDENCE OF RATE CONSTANT
FOR UNITED CATALYST G-91 (PELLETS)

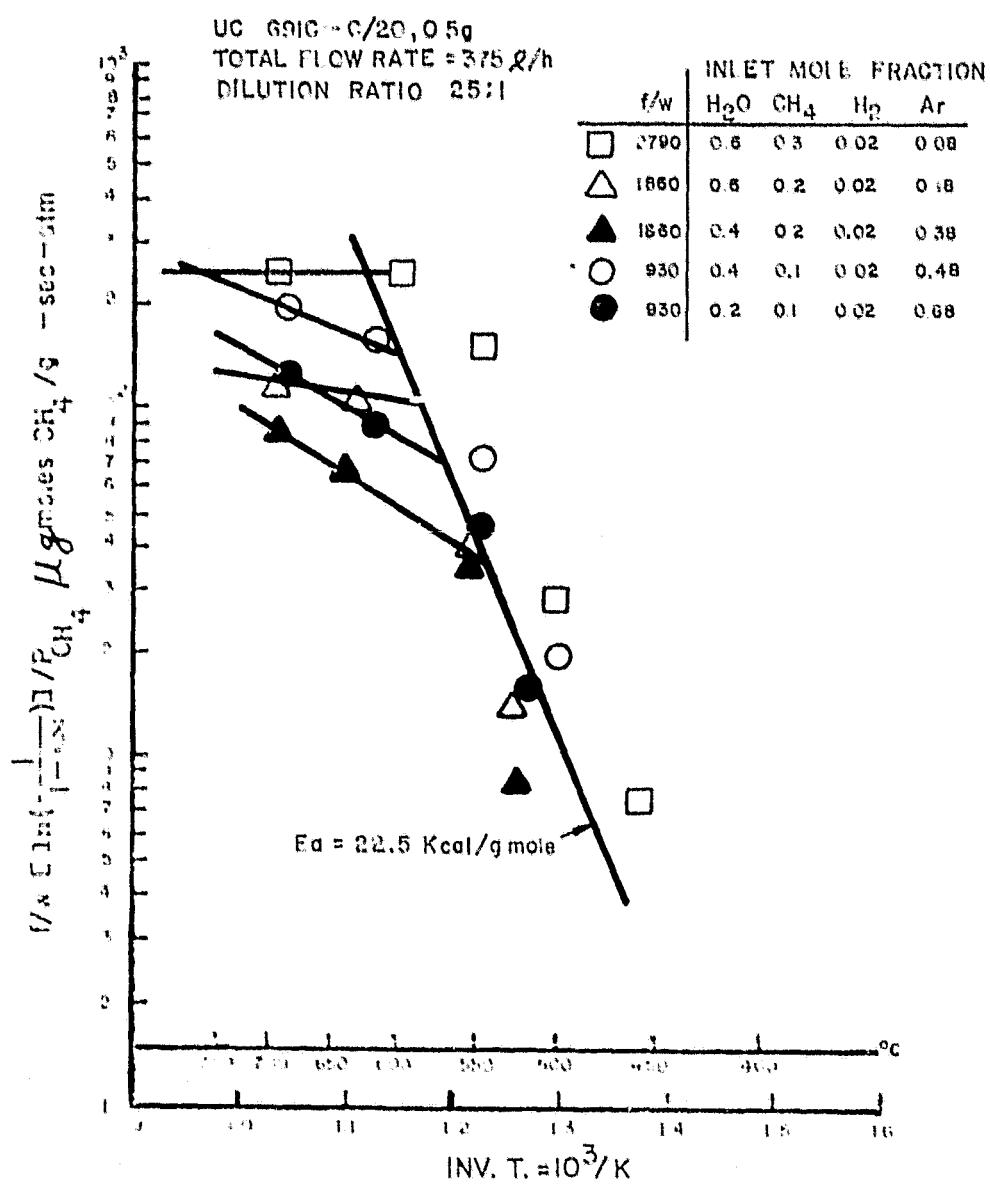


Figure 9 - TEMPERATURE DEPENDENCE OF RATE CONSTANT FOR UNITED CATALYST G-91 (CRUSHED)

D1312

UC-C-II-9-02/16-20 MESH

0.5 g

Total Flow Rate = 375 cm^3/hr

Dilution Ratio = 25 : 1

$\frac{f}{w}$	Inlet Mole Fraction				DATE of TEST
	CH_4	H_2O	He	H_2	
○ 930	0.1	0.2	0.68	0.02	7/16/80
● 930	0.1	0.4	0.48	0.02	7/17/80
△ 1860	0.2	0.4	0.38	0.02	8/4/80
▲ 1860	0.2	0.6	0.18	0.02	8/5/80
□ 2790	0.3	0.6	0.08	0.02	8/6/80

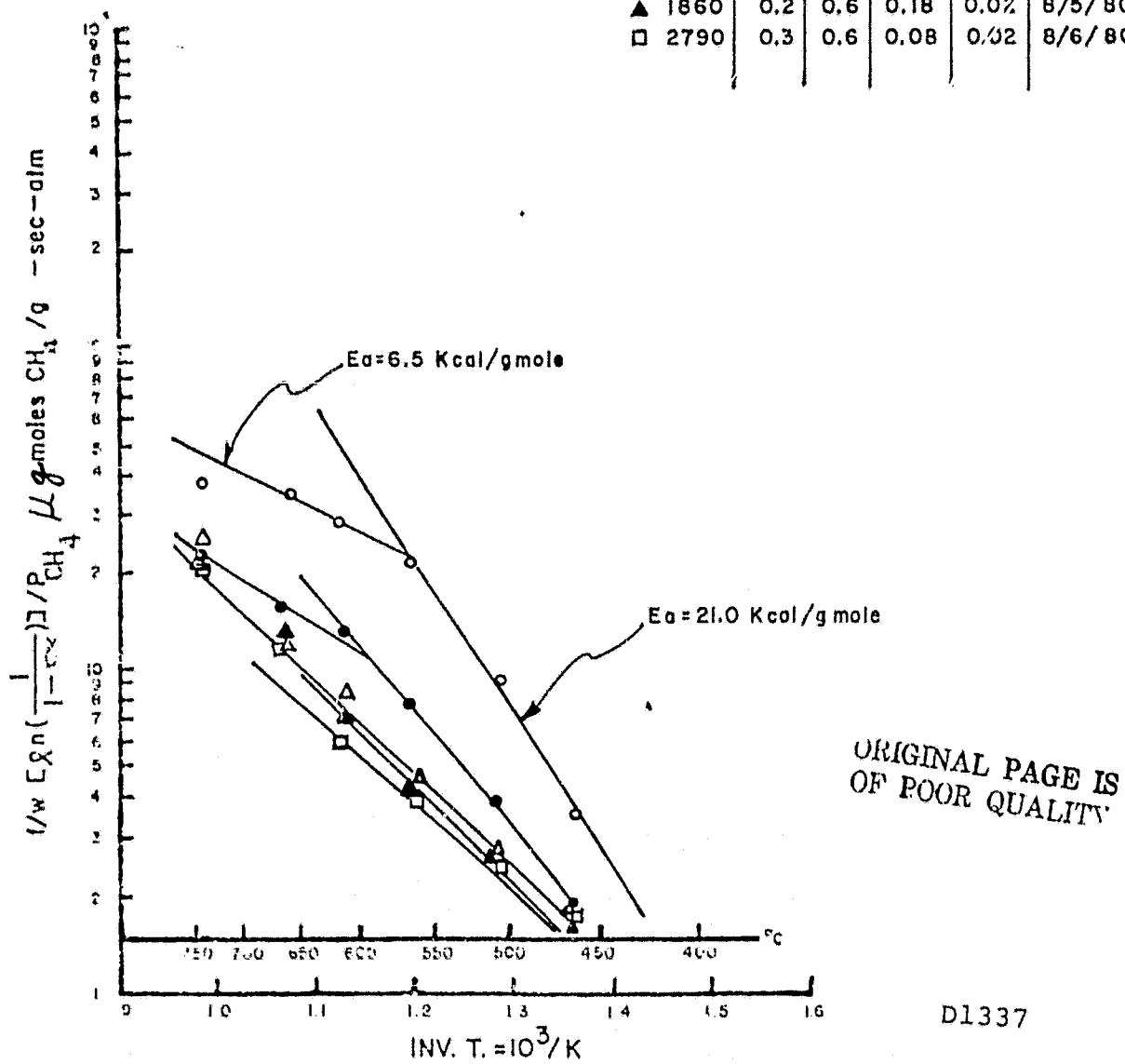
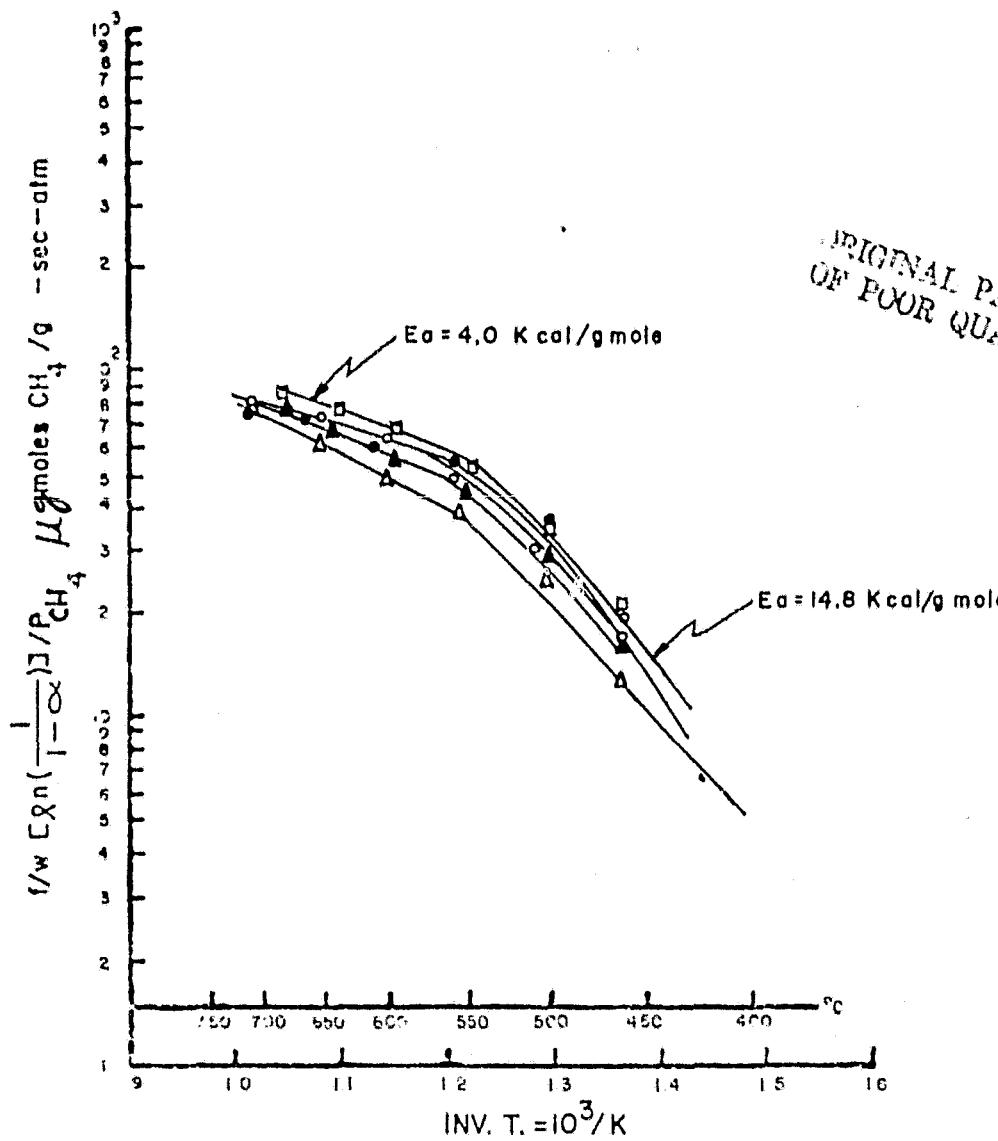


Figure 10 - TEMPERATURE DEPENDENCE OF RATE CONSTANT FOR UNITED CATALYST C-11-9-02 (CRUSHED)

UC-C-II-9-02/P
 3.0g
 Total Flow Rate = 375 l/hr
 Dilution Ratio = 5:1

f W	Inlet Mole Fraction				DATE of TEST
	CH ₄	H ₂ O	He	H ₂	
□ 465	0.3	0.6	0.08	0.02	8/8/80
▲ 310	0.2	0.6	0.18	0.02	8/11/80
△ 310	0.2	0.4	0.38	0.02	8/12/80
(Catalyst Regenerated)					
● 155	0.1	0.4	0.48	0.02	8/13/80
○ 155	0.1	0.2	0.08	0.02	8/14/80



D1338

Figure 11 - TEMPERATURE DEPENDENCE OF RATE CONSTANT
 FOR UNITED CATALYST C-11-9-02 (PELLETS)

Inlet Mole Fraction

f_w	H_2O	CH_4	H_2	He
195	0.4	0.1	0.02	0.48

Katalco 23-1
(Pellet, 2.38g)
Total Flow Rate = 375 ℓ/hr
Dilution Ratio = 10:1

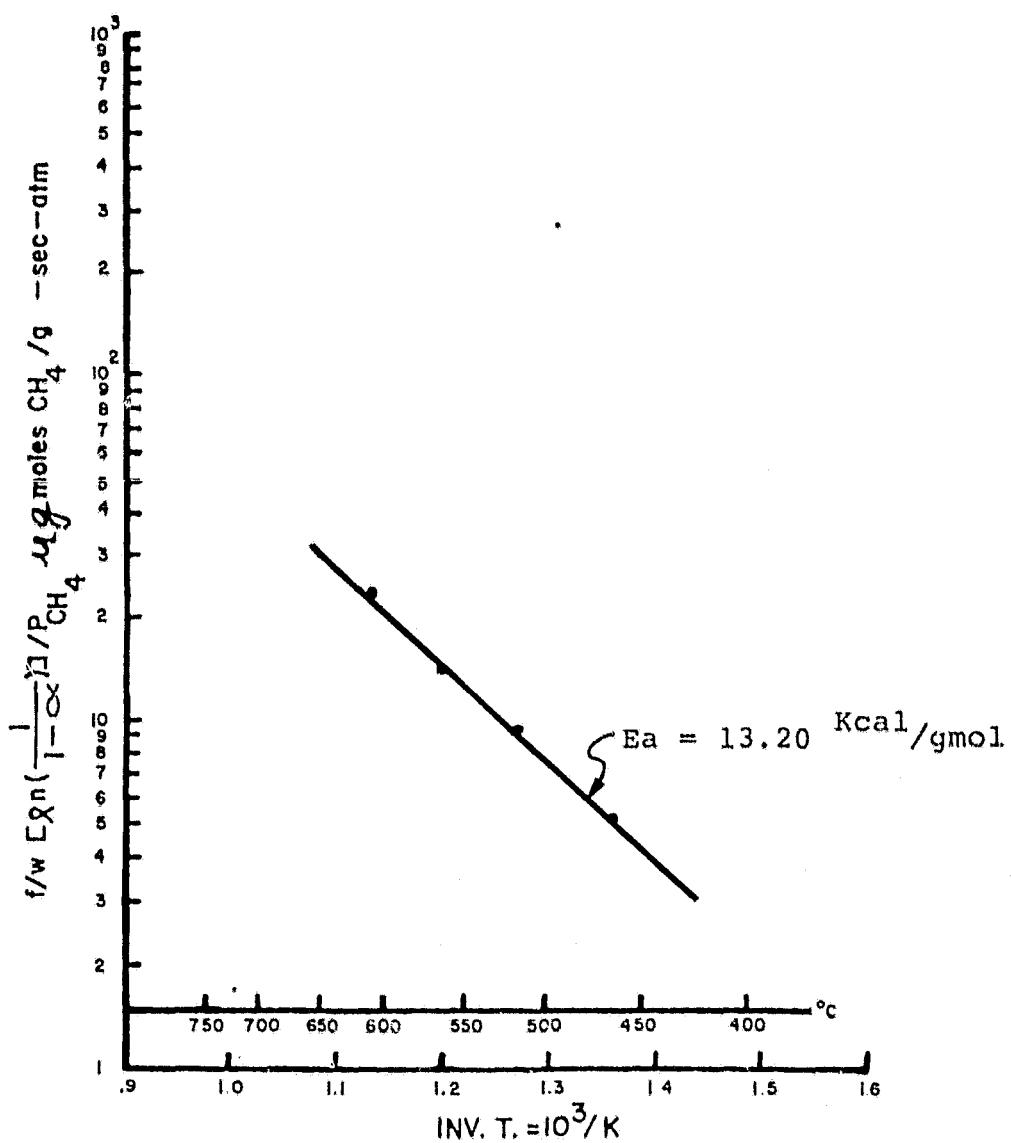


Figure 12 - TEMPERATURE DEPENDENCE OF RATE CONSTANT FOR KATALCO 23-1 (PELLETS)

TABLE VII COMPARISON OF DIFFERENT CATALYSTS ON METHANE REFORMING

CATALYST			ACTIVATION ENERGY, kcal/gmol		$\Delta T, ^\circ C$	Activity, $\mu\text{gmol/g-atm-sec}$
No.	Form	Sugg. Temp, $^\circ C$	Type	Diffusion - Free	Diffusion - Limited	Radial
100	Reduced	400-870	Crushed	17.5	6-9	+4
			Pelleted	16.5	6-9	+8
UC G-91	Oxidized	400-850	Crushed	22.5	1-9	-4
			Pelleted	20.0	2-9	-1
UC C-11-9-02	Oxidized	400-850	Crushed	21.0	4-8	-2
			Pelleted	14.6	4-8	-5
Katalco 23-1	Oxidized	400-1040	Crushed	-	-	-
			Pelleted	13.2	-	+1
35						

 $\Delta T = T_w - T_b$

Tw = Reactor Wall Temperature

Tb = Reactor Bed Temperature

Crushed particle = 16-20 mesh (0.5mm)

1. Catalyst 100 has considerably higher activity (150 $\mu\text{gmol/g-atm-sec}$ at 500°C) in both crushed and pelleted particles than the other three catalysts (10 to 60 $\mu\text{gmol/g-atm-sec}$ at 500°C).
2. Catalyst 100 is the only one of the four catalysts which has been reduced by the manufacturer. Thus the hydrocarbon feed can be admitted after a short reduction period. The other three catalysts were given a longer reduction period (as high as ~16 hours) since they are in oxidized form.
3. There is no significant difference in the catalyst activity of the crushed and pelleted catalysts for Catalyst 100. This fact suggests that the catalyst is uniformly distributed in a pellet and the diffusion resistance into the catalyst pores is negligible. For the other three catalysts, the pelleted catalysts have higher activity than the crushed catalysts. This suggests that the catalyst is not uniformly distributed in the pellets.
4. The UC G-91 and UC G-11-9-02 catalysts had a small negative temperature gradient (i.e., the reactor bed temperature was higher than the reactor wall temperature). Although this is contrary to expectation it is not unusual in this kind of test and does not affect the results.

5. As shown by the data in Figures 8 and 9, the activity of UC C-11-9-02 (especially for the crushed catalysts) decreased with time, i.e., the catalyst was deactivated and aged significantly.
6. Kataeo 23-1 catalyst has the lowest activity of the four catalysts tested. The crushed particle activity was too low to be measured even with twice the usual reactor charge. The pelleted catalyst has an activity of 10 $\mu\text{gmol/g-atm-sec}$ at 500°C compared to 60 $\mu\text{gmol/g-atm-sec}$ and 30 $\mu\text{gmol/g-atm-sec}$ for UC G-91 and UC C-11-9-02 catalysts respectively.

- Kinetic Data Base

The test results obtained with the four commercial catalysts lead to the following conclusions:

1. At temperatures below 600°C, the reaction can be assumed to be a simple first-order reaction with respect to methane:

$$R = K \cdot P_{\text{CH}_4}$$

Where,

$$k = k_0 \cdot \exp(-E/RT)$$

For Catalyst 100,

$$E = 17.0 \text{ kcal/gmol}$$

$$k_0 = 1.10 \times 10^7 \text{ } \mu\text{gmol CH}_4/\text{g-atm-sec}$$

2. At temperatures between 550 and 600°C, a mass diffusion (mainly external) begins to control the reaction.
3. In the absence of the catalysts, the decomposition of methane and the reaction of methane with steam was negligible with the aluminum oxide support only.

4. At temperatures higher than 600°C, the combination effect of internal and external mass diffusion may alter the rate of reaction and possibly the rate expression. The data collected below 600°C are adequate for initial modeling of the subseale reactor.

4.4 Ancillary Subsystem Data Base

4.4.1 Burner Development

As explained in Section III, operation of the burner test rig, expected for late August, has been delayed.

Commissioning work on the fuel and purge gas supply system was completed. This system, shown in Fig. 13, incorporates the appropriate check valves and safety solenoid to provide for system shutdown on flame failure and to prevent inadvertent mixing of fuel gas and purge gas. The completely wired and electrically energized reformer burner control panel is shown in Fig. 14, and the flexible high temperature (400 to 500°C) fuel gas and air supply connections to the burner are shown in Fig. 15. This 60 kW (1/2 of the burner length required for a 120 kW DC system) capacity burner element is full scale width and depth, and will be subjected to a series of 20 minute flame stability tests as summarized in Table VIII of Quarterly Report No. 3. The operating procedure and shutdown procedures to be followed for each 20 minute test are given in Tables VIII and IX. Testing will begin by mid-October on the reformer burner.

4.4.2 Water Conditioner Development

Studies comparing costs for suitable quality boiler feed water from spent air derived condensate and from tap water were completed during this quarter. The processing of condensate recovered from spent air and fresh fuel will be more economical than tap water processing in the majority of cities. Further, if phosphoric acid partial condensation can be done effectively, and if suitable disposal or re-use of the acid so removed can be arranged (see Section 4.2 of this report), recovered condensate will be more economical to process in all but a very few urban areas.

The water cost comparison studies included:

1. An overall examination of the public water supplies of the 100 largest cities in the United States for ionic composition and ranges of constituents (based on 1962 data).

Purge/ Preheat Subsystem

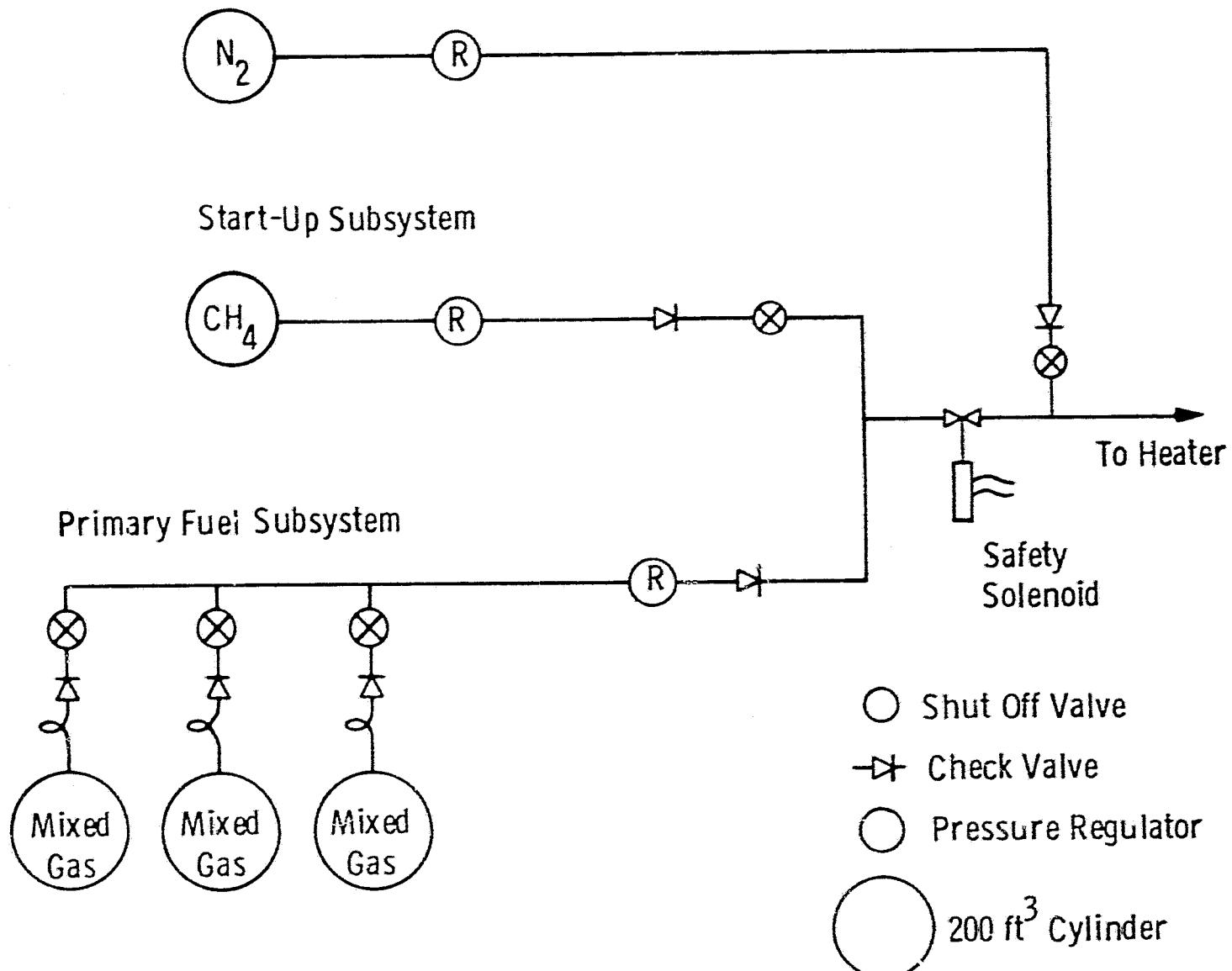


Figure 13 - Fuel System Schematic

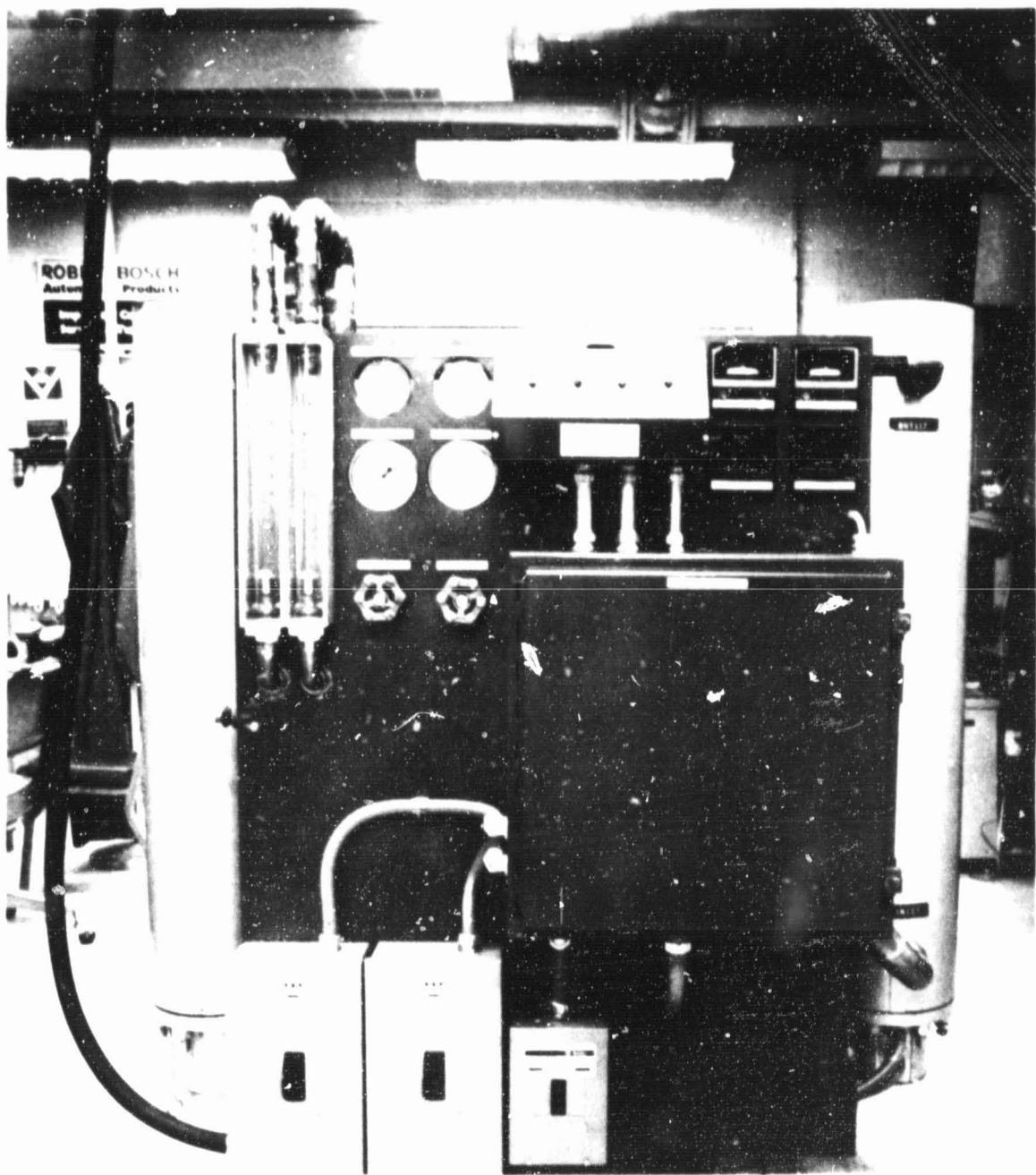


Figure 14 - Reformer Burner Control Panel

Original Photo

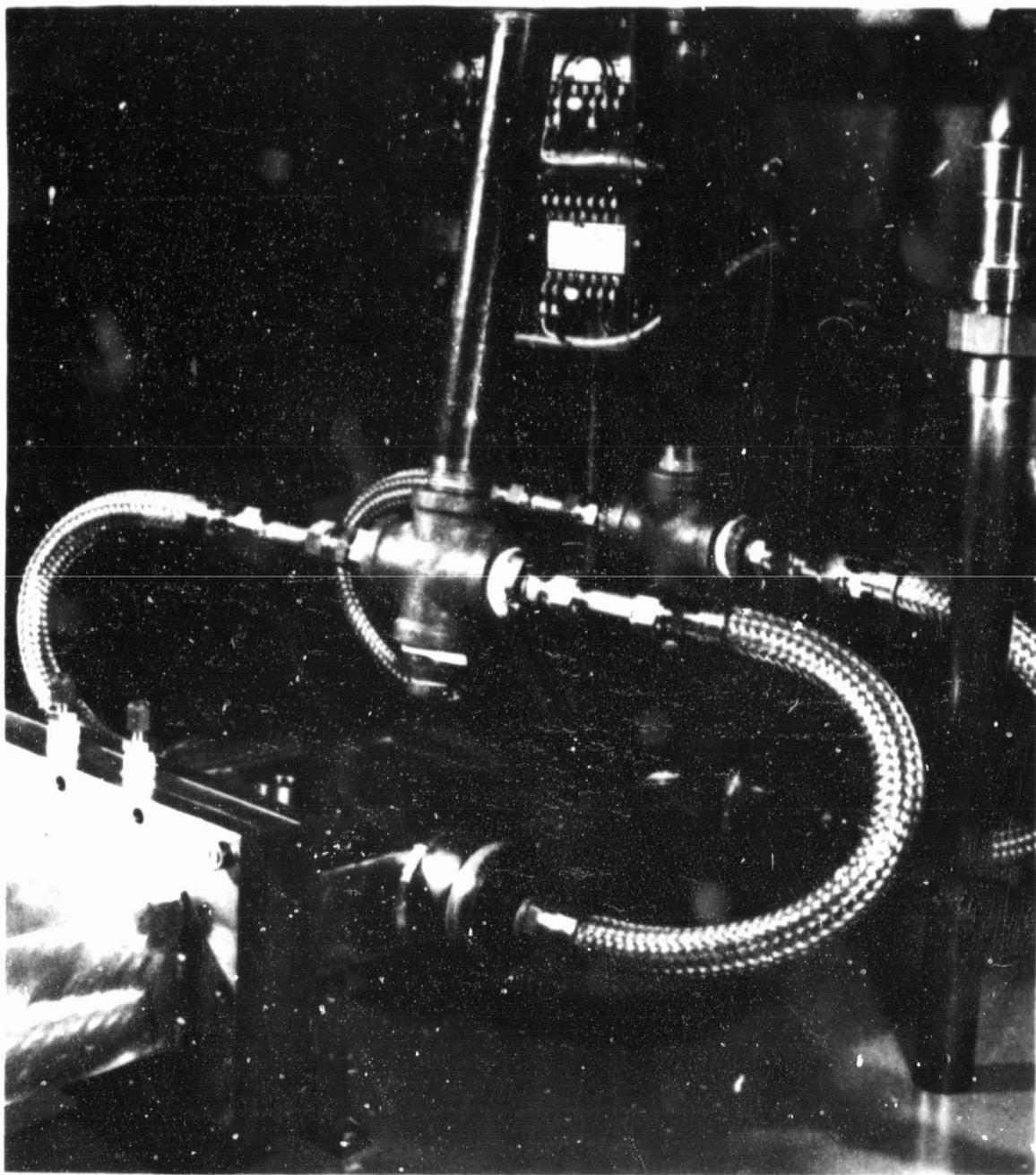


Figure 15 - Reformer Burner

TABLE VIII
Reformer, Burner Operating Procedure

Gas Bottles		
● Nitrogen	OFF	
● Methane	OFF	
● Fuel Gas	OFF	
Gas Isolation Valves		
● Nitrogen	ON	
● Methane	OFF	
● Fuel Gas	OFF	
Control Panel Power	ON	
Combustion Air		
If combustion air blower is to be used		
● House Air Shutoff Valve	OFF	
● Blower Shutoff Valve	ON	
● Blower Breaker	ON	
● Air Flowrate	25%	
If house air system is to be used		
● Blower Shutoff Valve	OFF	
● House Air Shutoff Valve	ON	
● Air Flowrate	25%	
Fuel System		
● Nitrogen bottle	ON	
● Nitrogen pressure regulator	50 PSIG	
● Nitrogen flow rate	25%	
Cooling Water		
● Control Valve	ON	
● Flowrate	5 GPM	
Air Preheat System		
● Air Heater Breaker	ON	
● SCR Temperature	800°F	
● Over Temperature Switch	900°F	
Fuel Preheat System		
● Fuel Heater Breaker	ON	
● SCR Temperature Controller	800°F	
● Over Temperature Switch	900°F	
Preheat Systems Ten (10) Minutes		

TABLE VIII (Cont'd)

Ignition System		
● Transformer Switch	ON	
● Verify spark	--	
Burner Ignition		
● Natural gas Isolation valve	OPEN	
● Natural gas supply valve	OPEN	
● Natural gas regulator	20 PSIG	
● Safety Solenoid Bypass Switch	ON	
● Nitrogen Isolation valve	OFF	
Verify Ignition		
If positive		
● Safety solenoid	ON	
● Safety solenoid bypass switch	OFF	
● Nitrogen bottle	OFF	
If negative		
● Nitrogen isolation valve	OPEN	
● Gas supply valve	OFF	
● Purge		
● Repeat steps "fuel system" through "burner ignition"		
Reformer Gas System		
● Mixed gas isolation valve	OPEN	
● Mixed gas bottle	OPEN	
● Mixed gas pressure regulator	50 PSIG	
● Natural gas isolation valve	CLOSED	
● Natural gas bottle	OFF	
Transformer Switch	OFF	

TABLE IX
Reformer Burner Shutdown Procedure

• Nitrogen pressure regulator	50 PSIG
• Nitrogen Isolation valve	OPEN
• Fuel pressure regulator	0 PSIG
• Fuel bottles	CLOSED
• Safety Solenoid Switch	OFF
• Air Preheat Temperature	70°F
• Air Heater Breaker	OFF
• Air Preheat Temperature	70°F
• Fuel Heater Breaker	
Purge System for ten minutes or until heater discharge temperatures are at 100°F.	
• Cooling Water Control Valve	OFF
• Nitrogen pressure regulator	0 PSIG
• Nitrogen bottle	OFF
• Nitrogen Isolation Valve	OFF
• Air Supply	OFF

Emergency Shutdown Procedure

- Emergency Fuel Switch OFF
- Air Heater Breaker OFF
- Fuel Heater Breaker OFF

2. An in-depth examination of 18 of the 100 largest cities for composition and specific ionic make-up of finished municipal waters.

3. Costs for processing water.

These are described below.

Overall Examination of Water Supplies From 100 Largest U.S. Cities

The finished water supplies of the 100 largest cities in the United States (1962) were reviewed, as a group, and summaries taken from the literature were presented in the Monthly Technical Progress Narrative No. 8. Included were constituents, properties, quality and analyses. The dissolved solids content of the feed water establishes ionic concentrations, which in turn establish ion exchange resin requirements. Since the ion exchange operation is by far the most expensive operation in upgrading water to boiler feed water quality, the dissolved solids content is most significant in determining water processing costs. The median dissolved solids content of the tap water of the 100 largest U.S. cities was 186 ppm. A summation of the individual ionic median values, converted to a CaCO_3 basis, gave totals of 85 ppm, as CaCO_3 , for the anions and 118 ppm, as CaCO_3 , for the cations. This compared to a recovered condensate anion content of 107 ppm PO_4^{3-} , as CaCO_3 from spent air with 0.5 ppm P_2O_5 content. Thus, recovered condensate has an anion content, which is about equal to the median anion content of the 100 largest cities. This was examined further as part of the indepth study of 18 of the 100 cities.

In-Depth Examination of Water Supplies From 18 Representative U.S. Cities

An in-depth examination was made of the public water supplies of 18 of the 100 largest cities. These were selected to be representative of the tap water range over the entire country. Four ranges of dissolved solids were used, which were consistent with those used in the literature. Only a few water supplies have less than 100 ppm or greater than 500 ppm total dissolved solids. This then defined two of the ranges. The remaining two are divided between 100 and 500 ppm. Representative cities which were selected for different ranges of total dissolved solids are

shown in Table X. Many of these cities obtain and process water from several sources. The source providing the greatest percent of finished water was used in the detailed studies. Also, there is usually considerable variation in water compositions for samples taken during different times of the year. Ten of the samples considered were taken during July or August, three of the samples were taken during March and one each of the samples was taken during January, February, April, May and September. Fifteen cities obtained raw water from surface sources, two from wells and one from a combination. Finished water from Pittsburgh's Aspinwall plant had an average yearly analysis reported as well as the analysis of the spot sample, taken during March. The maximum and minimum analyses of constituents taken during the same year were also reported.

Chemical analyses of the finished water supplies of the selected eighteen U.S. cities are presented in Table XI. Values shown here were converted to ppm as CaCO_3 . This permitted checking the total major anions to cations balances and, at the same time, obtain estimates of ion exchanger loading rates. Two of the water supplies, for Houston and Lubbock, Texas, have large portions or all of their raw water taken from wells and the analyses vary considerably between the contributing wells, and between wells and surface source contributors. Therefore, results for these cities have also been reported as ranges. Analyses for Pittsburgh are shown for spot, average, maximum and minimum levels.

A summary and relative ranking of the anion contents of the finished water supplies of the 18 cities is shown in Table XII. Also shown for comparison is the estimated PO_4^{3-} level estimated for water obtained as recovered condensate. It can be seen that seven cities (or about 1/3), primarily in the northeastern part of the U.S., have anion contents lower than that estimated for recovered condensate. Total dissolved solids (TDS) contents, also included in Table XII, follow fairly consistently with increasing anion content.

Water prices were obtained for most of the water supplies being considered. These are shown in Table XIII. Two different levels of use

TABLE X

Representative U.S. Cities Selected for Different Ranges
Of Total Dissolved Solids In Finished Public Water Supplies

<u>TDS Conc. Range (ppm)</u>	<u>Selected Cities</u>
0-100	San Francisco, CA Boston, MA Albany, NY New York, NY
101-250	Denver, CO District of Columbia Miami, FL Chicago, IL Detroit, MI Buffalo, NY Philadelphia, PA Pittsburgh, PA
251-500	Los Angeles, CA Kansas City, KS Houston, TX
>500	Phoenix, AZ San Diego, CA Lubbock, TX

TABLE XII

Chemical Analyses of Eighteen U.S. Public Water Supplies
 NOTE: Results in ppm CaCO_3 Unless Otherwise Noted

	Cations					SiO_2 (ppm SiO_2)	Anions						Total Dissolved Solids (ppm)	Total Cations/Anions (ppm CaCO_3)	
	Fe	Mn	Ca	Mg	Na	K	CO_3	HCO_3	SO_4	Cl	F	NO_3			
1. Phoenix (Squaw Peak)	0.05	—	115	62	292	6.2	13	0	117	59	299	0.8	2.9	563	475/479
2. Los Angeles (San Fernando)	0.03	—	60	21	68	4.5	31	0	109	24	23	1.3	0.2	212	153/158
3. San Diego (Alvarado)	0	—	165	119	210	6.0	12	10	56	302	130	1.3	0.9	666	500/500
4. San Francisco (Hetch Hetchy)	0.08	0	8	3	6	0.5	2.7	0	9	1.6	5	0	0	27	17/16
5. Denver (Moffat)	0	0	25	9	6	0.5	7.5	0	23	20	0	2.1	0.3	39	41/45
6. District/Colum. (McMillan)	0	0	100	36	17	2.4	3.8	0	87	47	21	2.4	1.0	204	155/158
7. Miami (Orr)	0.13	—	56	8	—28—	—	7.0	1.7	37	25	23	2.6	0.2	110	86/90
8. Chicago (Chi. Av. Sta.)	0.13	0.16	80	45	8	1.0	1.3	0	105	21	11	2.6	0.3	149	134/140
9. Kansas City (Quindaro)	0	0	142	45	53	5.5	9.7	0	131	84	28	0.8	4.6	311	246/248
10. Boston (Norumbega)	0.11	0	11	2	5	1.0	3.1	0	7	7	5	0	0	31	19/19
11. Detroit (Park Station)	0.16	0.05	70	29	8	1.0	1.5	0	77	20	13	0	0.3	131	108/110
12. Albany (Fuera Bush)	0.08	0	37	10	4	1.0	6.3	0	30	21	2.3	0	0.1	68	52/53
13. Buffalo (Filtr. Plant)	0.11	0	95	37	20	1.5	0.7	0	88	27	34	3.2	0.1	186	154/152
14. New York (Catskill/Dela.)	0.16	0	17	4	4	0.6	2.0	0	11	9	5.4	0	0.7	41	26/26
15. Philadelphia (Belmont)	0.16	0	55	28	15	2.8	9.4	0	21	53	20	2.1	5.4	139	101/102
16. Pittsburgh (Aspinwall)	0	0.44	42	18	15	2.3	5.3	0	3	55	16	0.8	1.6	110	78/76
17. Houston (San Jacinto)	0.08	0.27	52	7	23	2.3	6.1	0	21	27	38	0.8	0	129 (456-316)	85/87 (390/402-265/275) River
18. Lubbock (Sand Hills W.F.)	0	0	160	58	57	6.3	53	0	243	24	14	2.6	1.2	350 (861/350)	350 (281/285) Wells
Pittsburgh (max.)	0.8	4.6	120	62	80	—	8.0	—	16	197	65	2.9	2.8	402	267/284
Pittsburgh (min.)	0.3	0.2	35	21	25	—	5.2	—	3	58	18	2.1	1.3	122	82/82
Pittsburgh (avg.)	0.5	1.1	75	39	47	—	6.5	—	7	117	38	2.4	1.9	239	163/164
Houston (East End W.F.)	0.16	0	10	4	375	1.2	16	0	307	8	83	3.9	0	456	390/402
Myerland	0.43	0	57	21	184	2.3	20	0	207	12	54	2.1	0	316	265/275
Lubbock (Northeast W.F.)	0.05	0.02	177	255	224	19	53	0	266	247	162	7.9	7.7	861	675/691

TABLE XII
Summary and Ranking of Public Water Supplies by Anion Content

	Anion Content (ppm, as CaCO ₃)	TDS (ppm)
1. Lubbock, TX	(691-285)a	(861-350)a
2. San Diego, CA	500	666
3. Phoenix, AZ	479	563
4. Houston, TX	(402-275)a (87)b	(456-316)a (129)b
5. Kansas City, KS	248	311
6. Pittsburgh, PA	164 (Avg.)	239
7. Los Angeles, CA	158	212
8. District of Columbia	158	204
9. Buffalo, NY	152	186
10. Chicago, IL	140	149
11. Detroit, MI	110	131
$\text{PO}_4^{3-} \sim 107 \text{ ppm as CaCO}_3 - \text{recovered condensate}$		
12. Philadelphia, PA	102	139
13. Miami, FL	90	110
14. Albany, NY	53	68
15. Denver, CO	45	39
16. New York, NY	26	41
17. Boston, MA	19	31
18. San Francisco, CA	16	27

NOTES: a. only wells; b. only San Jacinto River.

TABLE XIII

Water Prices - 1978

City	Cost (\$/5.0 m ³)	Cost (\$/284 m ³)
1. Phoenix, AZ	0.968	0.402
2. Los Angeles, CA	1.457	0.731
3. San Diego, CA	0.793	0.793
4. San Francisco, CA	0.836	
5. Denver, CO	0.925	0.589
6. District of Columbia	0.694	0.694
7. Miami, FL	0.635	0.635
8. Chicago, IL	0.604	0.604
9. Kansas City, KS	1.285	0.766
10. Boston, MA	0.317	0.317
11. Detroit, MI	0.736	0.736
12. Albany, NY		
13. Buffalo, NY	0.934	0.314
14. New York, NY	0.926	0.926
15. Philadelphia, PA	0.738	0.450
16. Pittsburgh, PA	1.135	1.215
17. Houston, TX	1.159	1.123
18. Lubbock, TX	1.231	0.756

were selected, in order to bracket the approximately 50 m³ per month required. The costs of water ranged from approximately \$0.06 - \$0.28 per cubic meter for the 18 cities.

Water Processing Costs

Costs associated with the deionization of water are, as mentioned previously, the most significant in the entire purification train. These costs will vary according to whether

1. The user owns and operates the total ion exchanger, including regeneration of columns.
2. The user owns the ion exchange columns, but they are regenerated by an outside vendor.
3. An outside vendor owns, maintains and regenerates all ion exchange columns and provides these to the user on a rental basis.

Where unskilled or semi-skilled personnel are used to service the OS/IES unit, a user owned/vendor regenerated column agreement or a vendor owned/vendor regenerated column agreement are considered the most reliable arrangements. The complexities associated with regeneration of the ion exchanger columns are essentially eliminated. Operators need generally only concern themselves with replacement of spent columns with columns which have been externally regenerated by a supplier. Also, the handling of concentrated acids and bases, air supply sources for resin mixing, water supply sources for washing resins and disposal of wastes from the regeneration operations are eliminated.

Several suppliers of regeneration or rental services for ion exchange columns were contacted. To give the suppliers a specification, it was assumed that the ion exchange train consisted of a cation bed-anion bed-mixed bed, in series, that the feed water contained an anion loading of 171 ppm (as CaCO₃), and that the cation/anion bed combination discharged to the mixed bed at 50,000 ohm-cm, while the discharge from the mixed bed was at 1 megohm-cm. Operating costs for the ion exchanging of the feed water were estimated as follows:

Barnstead	\$0.048/Liter + Shipping costs
Millipore/Continental	\$0.045/Liter of columns
Culligan	\$0.0085/Liter

These values are approximate and will vary with the relative concentrations of different ions in the water. The Culligan rental arrangement was subsequently used, at a different anion loading, for additional cost calculations. In order to compare costs for producing suitable quality reformer-boiler feed water from recovered condensate and tap water, the costs of attendant processes and materials were estimated. It was assumed that the concentrations of total exchangeable anions in both waters was the same at 107 ppm as CaCO_3 . Several operations could not be costed because of their dependence on system design and equipment configuration. Since these operations were common to the processing of both types of water and because of the dominance of the cost of ion exchanging, their proportionate contributions were not considered significant. The estimated costs were as follows:

<u>Operation/Material</u>	<u>Cost/cubic meter</u>	<u>Water Type Used With</u>
Chlorine Removal	\$ 0.015	Both(a)
Pre and Post Filtering	\$ 0.049	Both(b)
Ion Exchanging	\$ 5.28	Both
Tap Water	\$ 0.29(c)	Tap Water
Degasification	--	Both
Pumping	--	Both

- (a) Used with recovered condensate for removal of organics; GAC changed yearly.
- (b) Four cartridge changes per year.
- (c) Public water costs ranged \$0.063 - \$0.29 /cubic meter

SUMMARY AND CONCLUSIONS

The removal of dissolved solids by ion exchanging is the controlling factor in the overall costs for processing the required quality reformer-boiler feed water. Using tap water instead of recovered condensate can add 1-5% to this cost. Other processing costs are relatively small and add very little to the overall cost. Ion exchanging costs vary directly with the concentrations of exchangeable ions. With equal concentrations of exchangeable ions, costs for processing tap water and recovered condensate would be approximately the same. With a low phosphoric acid content in recovered condensate as discussed in Section 4.2 of this report, the use condensate would be more economical than tap water in all but a few cities (such as New York or Boston) and, in these cities, the cost differential would not be sufficient to justify a special design. Public water supply compositions vary considerably with the time of the year. The chemical analyses of the water from 18 of 100 largest U.S. cities, mostly on spot samples, showed that only one third of these had lower total exchangeable anion concentrations than that of the recovered condensate. Therefore, the cost of processing condensate will be more economical in the majority of cities. The exceptions are cities in the northeastern part of the U.S. The use of tap water as a backup source for producing a suitable quality reformer-boiler feed water is a viable alternate for emergency and short term operation.

The use of rental or vendor regeneration of user owned ion exchange columns appears to be the most desirable alternative for coping with unskilled or semi-skilled equipment operators of water purification equipment.

4.4.3 Other Ancillary Systems Development

Heat Exchangers

Several meetings with shell and tube (American-Standard) and formed plate (Harrison/G-M) exchanger vendors were held. Now that data are available (Section 4.2 of this report) to permit completion of heat exchanger performance specifications, both vendors have agreed to respond

to such specifications with size and cost information which will be used in the conceptual design of a prototype OS/IES unit. Both vendors are confident of their ability to adapt standard, low cost designs for our application.

An engineer was assigned to complete the performance specifications, and our Purchasing Department has assigned one of their agents to process requests for quotation. The exchanger performance specifications will be issued during the next quarter.

Control System

Start-up, shut-down, and load transients are presently being analyzed to define the controls required for the system shown in Figure 7. Sequence lists will be prepared for each of the conditions being addressed. All control functions will be shown on the P&ID.

The sequence list and control function definition will be completed during the next quarter.

Steam Jet Ejector

As shown on the P&ID* (Figure 7), a natural gas booster blower (Item CP-2) will move reactant gases through the OS/IES system. A steam jet ejector, as used by UTC for moving natural gas, has proven to be more difficult to design for OS/IES than we had anticipated. The technical paper "Optimum Design of Ejectors Using Digital Computers," L. A. DeFrate and A. E. Hoerl (Chemical Engineers Progress Symposium Series #21, 1959) was obtained during this quarter. It presented a set of complicated equations for the jet area-entrainment ratios.

* Process and Instrumentation Diagram

These are best solved by computer. However, the program to do so is not available to us, and the complexities of designing a manufacturable ejector suitable for start-up, low load, rapid up-load transients, and overload would require an effort beyond the intended scope of our present work. During the next quarter, we will prepare a performance specification for the ejector, and submit it to the Penberthy Division of Houdaille Industries, Inc. They "will design and produce the special ejectors needed" where standard units "are not capable of meeting operating requirements." The quotations were provided from the Penberthy Model 1-A ejector catalog provided to us by M. S. Jacobs Inc., the local Pittsburgh representatives of Penberthy. During the coming quarter we will develop information through Mr. Robert Ellis in Penberthy's home office at Prophetstown, Illinois.

4.7 Prototype Conceptual Design

As shown in Figure 7 , Section 4.2 of this report, a 120 kW DC system design has been developed. It includes two reformer reactors, each sized for one half of the total duty. As indicated in Section IV, Plans, of the Quarterly Report No. 3, an engineering specialist familiar with high temperature gas cooled nuclear equipment design was assigned to evaluate 60 kW reformer reactor design concepts. He has produced a concept in Westinghouse Disclosure No. AL 80-22. It incorporates a modular concept that can use the diffusion burner design discussed in Section 4.4 to burn spent fuel to provide heat to one side of a catalyst containing passage. The other side of the passage is heated by reaction products. The concept will be reviewed in October with appropriate ERC engineers, and will be used to initiate a piping and structural layout and stress analysis program with Westinghouse manufacturing development engineers during the next quarter.

TASK 5: MANAGEMENT REPORTING AND DOCUMENTATION

5.1 Supervision and Coordination

Several meetings and informal discussions among members of the NASA technical management team and Westinghouse and ERC personnel were held during the National Fuel Cell Seminar. The meetings dealt with the need to prepare plans for future phases, coordination of the ERC Technology Contract, the direction of the Fuel Conditioning Task, and the design, fabrication and testing of fuel cell stacks for this program.

A talk based on the System Study of Phase I was presented at the National Fuel Cell Seminar.

A meeting to review the data on early efforts to produce cooling plates for Stack 559 and select the most attractive procedure for continuation of this effort was held. The procedures selected produced flat cooling plate halves which were successfully assembled.

Since fabrication of Stack 559 was delayed by the cooling plate problem, we decided to use the ERC proprietary matrix (Mat-1) instead of Kynol as originally proposed.

Under their parallel technology program, ERC conceived and made substantial progress on the heat treatment of bipolar plates. When it became clear that there would be a time lapse before the contract for the technology program continuation would be signed our NASA Project Manager suggested that experiments on heat treating of cooling plates and bipolar plates of the MK-2 configuration be carried out under this contract and this is being done. A meeting to review the status of and data on heat treatment with NASA Project Manager was held and resulted in an agreement to heat treat the bipolar plates, and end plates and cooling plates of Stacks 560 and 562.

Preliminary discussions of the technology to be used in and the fabrication schedule for the first 8 kW stack were held.

Participants in the fuel conditioner and large scale stack design tasks were informed of recent changes in fuel cell technology (e.g. heat treated plates) and operational requirements for incorporation in their work.

A meeting to ensure continued coordination of the Westinghouse and ERC work on stack mechanics was held. A joint meeting among people working on this contract and an in-house Westinghouse technology program was held to ensure that the work is coordinated.

An increase of \$1,000,000 (from \$1,551,000 to \$2,551,000) in funds allocated to this program was requested from and approved by the NASA Contract Specialist.

5.2 Documentation and Reporting

Technical Reports

The Third Quarterly Report (April-June) and the July and August monthlies were submitted for NASA approval. The Quarterly was distributed when approval was received and the two monthlies will be distributed when approval is received. The April and May monthly were distributed during this quarter when NASA approval was received.

Management Reports

The management reports (533M and 533P) for June, July and August were prepared and distributed according to the contract requirements.

The financial plan for the fifth quarter (533Q) was prepared and submitted.

5.3 Planning

After discussion with the NASA Project Manager, an IWR (Inter Works Requisition) to cover work on planning and continuation of this program was issued to the Westinghouse AESD (Advanced Energy System Division). This division has extensive experience in planning and managing large complex programs and has the charter to implement

commercialization of systems which are conceived and/or developed at the R&D Center. Work under this IWR began in September and should be completed by the end of calendar year 1980.

III. PROBLEMS

Assembly of Stacks 559 and 561 were delayed by the cooling plate and acid feed problems discussed in Section II. This in turn will result in a "clogging" of the pipeline and a delay in the test plan. The procedures defined for producing the cooling plates appear to have been successful and resolution of the acid feed problem was imminent at the end of this report period.

Assembly of Stack 560 and 562 will be delayed by the machining problem discussed in Section II. Machining of the needed plates was in progress at the end of this report period.

The preparation of the burner test plan and procedure documents required for the mandatory safety review delayed rig startup. Those documents have been prepared and submitted to the site safety committee (and as this is being written in early October, the test rig has passed its safety review).

IV. PLANS

TASK 1: DESIGN OF LARGE CELL STACKS

An analysis of the distribution of the stack compression forces between the active cell area and the boundary or shim area using the recently acquired material data is underway. Available data on the effects of stack compression or performance will be reviewed and correlated with the model.

A review meeting among NASA, ERC and Westinghouse members of the project team will be held to finalize the design of Stack 561. The acid feed scheme and the use of heat treated plates will be primary considerations.

The temperature profile data obtained on Stack 559 will be used to verify the Detailed Analytical Model.

TASK 2: STACK FABRICATION

Methods for assembling heat treated cooling plates will be investigated.

Components for Stacks 560, 561 and 562 will be fabricated and the stacks will be assembled when procedures and designs have been approved by the NASA Project Manager.

TASK 3: STACK TESTING

Immediately following pretesting Stack 559 will be installed and tested in the OS/IES simulation loop. The primary purpose of these tests will be to obtain temperature profile data with the innovative cooling plates under OS/IES operating conditions. This information will verify and be used in fine tuning of the detailed analytical model.

Tests of Stack 425 in the OS/IES will be terminated and a post test analyses performed to determine the cause of the anomalous performance of the one cell.

The 2 kW Test Facility will be commissioned and a stack (possibly 425) will be installed to permit a final check out of the system with an operating stack.

Construction of the 8 kW Test Facility will continue.

TASK 4: FUEL CONDITIONER DEVELOPMENT

The analysis of the system performance and control requirements will continue.

Reforming Catalyst Aging Tests and CO Shift Converter Catalyst Tests will be initiated as summarized in Tables XIV and XV.

TABLE XIV
PLAN FOR CO SHIFT CATALYST TEST

Catalyst = UC C-18HC (Low Temperature Shift Catalyst)

Weight = 0.5 to 1.0g, pelleted and crushed

Dilution Ratio = 15 to 20

Total Flow Rate = 300 l/hr

Total Space Velocity = $\sim 300,000 \text{ hr}^{-1}$

Dry Gas Composition = 0.8 H₂, 0.1 CO, 0.1 CO₂

Steam/Gas (S/C) Ratio = 0.4(2), 0.6(3), 0.8(4), 1.0(5), 1.2(6)

Temperatures, °C = 149, 177, 204, 232 and 260.

TABLE XV
PLAN FOR REFORMING CATALYST AGING TEST

Catalyst = Catalyst 100

Catalyst Bed = 2.5 x 3.7 cm (volume = 19.31 cc)
SV (CH₄) = 1500 hr⁻¹

Temperature - Time Sequence 400 hrs at 600°C
 400 hrs at 700°C
 400 hrs at 500°C
 400 hrs at 600°C

Steam/Carbon Mole Ratio = 2.5

Hydrogen/Carbon Mole Ratio = 0.1

Flow Rate	CH ₄	H ₂	H ₂ O	Total	S.V.Total
Liter/min (gas Phase)	0.483	0.0483	1.207	1.738	5400
gram/min	0.345	0.00432	0.966	1.315	-

Theoretical Volume Hydrogen Out = 0.931 lpm

Equilibrium composition at 600°C for CH₄ Conversion of 70%

Wet Gas Mole Fraction =	CH ₄	0.061
	H ₂ O	0.282
	H ₂	0.518
	CO	0.059
	CO ₂	0.080

TASK 5: MANAGEMENT AND DOCUMENTATION

5.1 Supervision and Coordination

Coordination of efforts among the task leaders and between FRC and Westinghouse will be continued.

Technical review meetings will be held at the convenience of the NASA Project Manager and presentations to and meetings with DOE personnel will be scheduled as requested.

5.2 Reporting and Documentation

The task leaders' inputs to the Technical Status Reports will be edited and the reports will be submitted to the NASA Technical Manager for patent approval. The management reports will also be prepared and submitted to the NASA Project Manager.

This report will be distributed when approved by the NASA Project Manager.

5.3 Planning

As described in Section II, this work is being done by the Westinghouse Advanced Energy Systems Division and is expected to be essentially complete during the next quarter. As the plan evolves, it will be reviewed with the NASA Project Manager.